New physics
and the Black Hole Mass Gap

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UC Davis, November 2020

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GW190521

The New York Times

These Black Holes Shouldn't Exist, but There They Are

FORBES.COM

LIGO's Biggest Mass Merger Ever Foretells A Black Hole Revolution

Astronomers detect super-rare type of black hole for the first time

BY SOPHIE LEWIS
SEPTEMBER 3, 2020 / 7:03 AM / CBS NEWS

NewScientist
IDEEËN DIE DE WERELD VERANDEREN

BLOGS DOSSIERS RECENSIES MAGAZINE AGENDA

Zwaartekrachtsgolven van 'te zware' zwarte gaten waargenomen

Latest Issues

SCIENTIFIC AMERICAN 175

LIGO and Virgo Capture Their Most Massive Black Holes Yet

Black holes: Cosmic signal rattles Earth after 7 billion years

By Jonathan Amos
BBC Science Correspondent

LIGO/Virgo's biggest discovery yet: the *impossible* black holes

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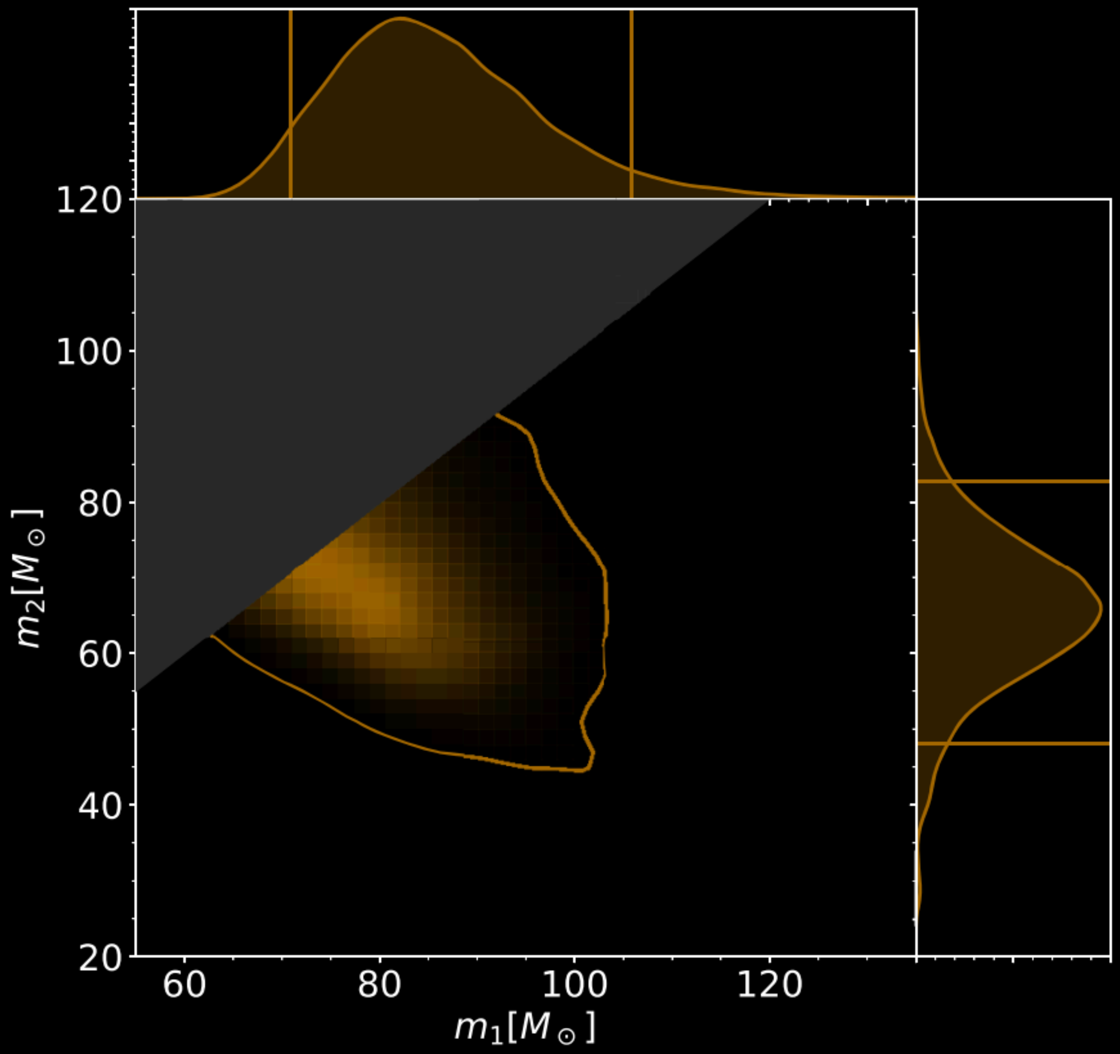

LIGO/Virgo's biggest discovery yet: the *impossible* black holes

From R. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), Phys. Rev. Lett. 125, 101102 (2020).

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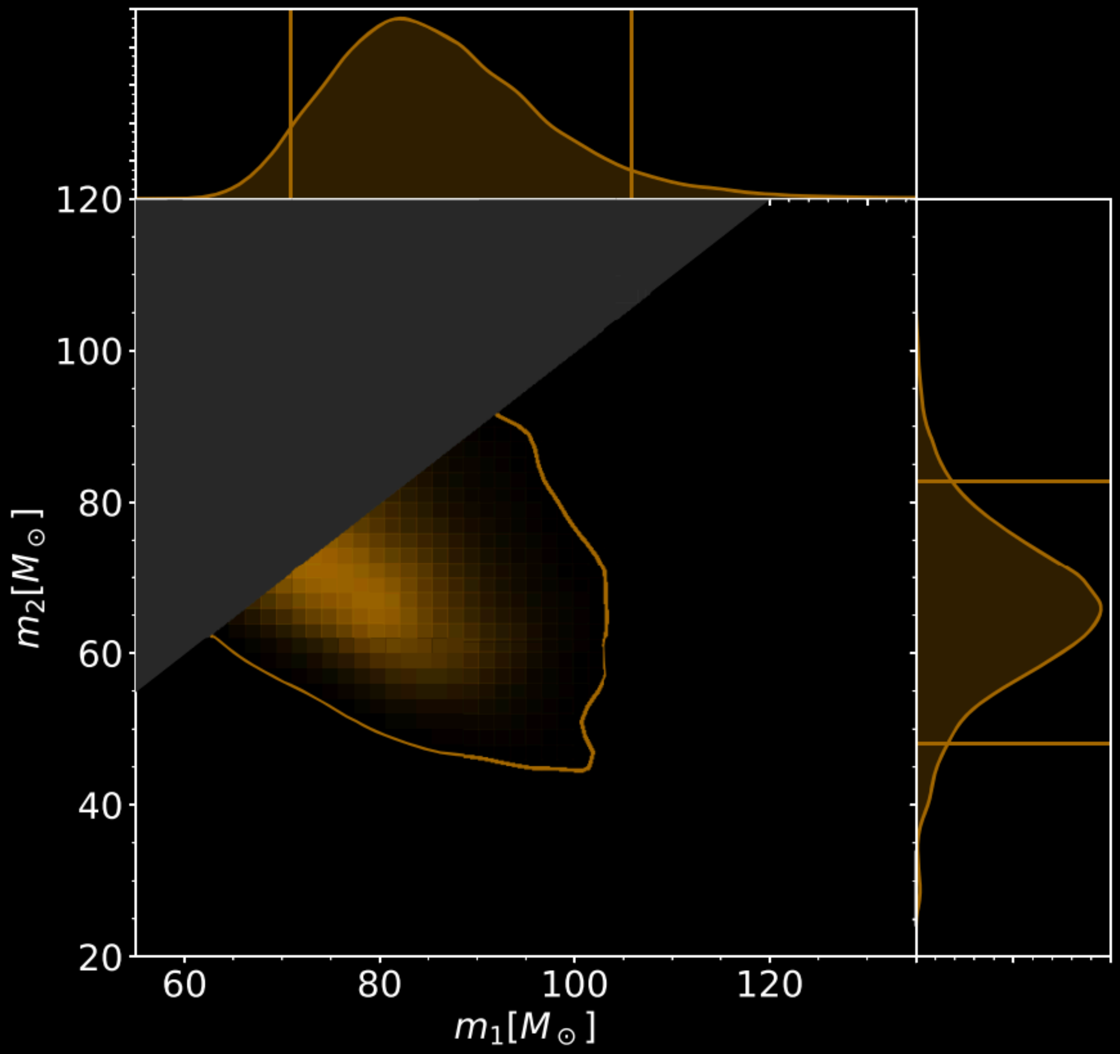


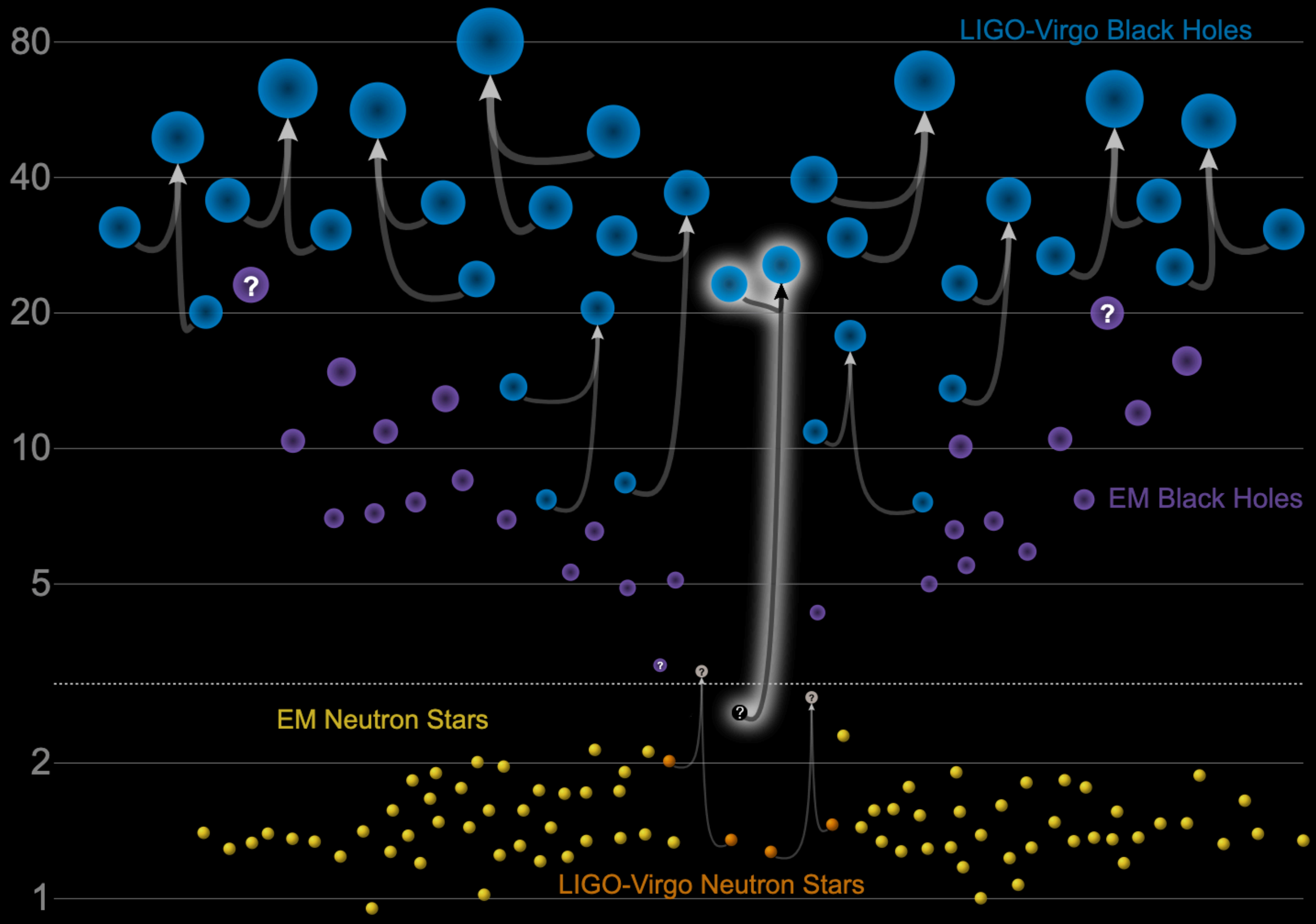
LIGO/Virgo's biggest discovery yet: the *impossible* black holes

… let's wind back a bit

From R. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), Phys. Rev. Lett. 125, 101102 (2020).

Binary mergers in LIGO/Virgo O1+O2

"The Stellar Graveyard"



Adapted from LIGO-Virgo, Frank Elavsky, Aaron Geller

Binary mergers in LIGO/Virgo O1+O2

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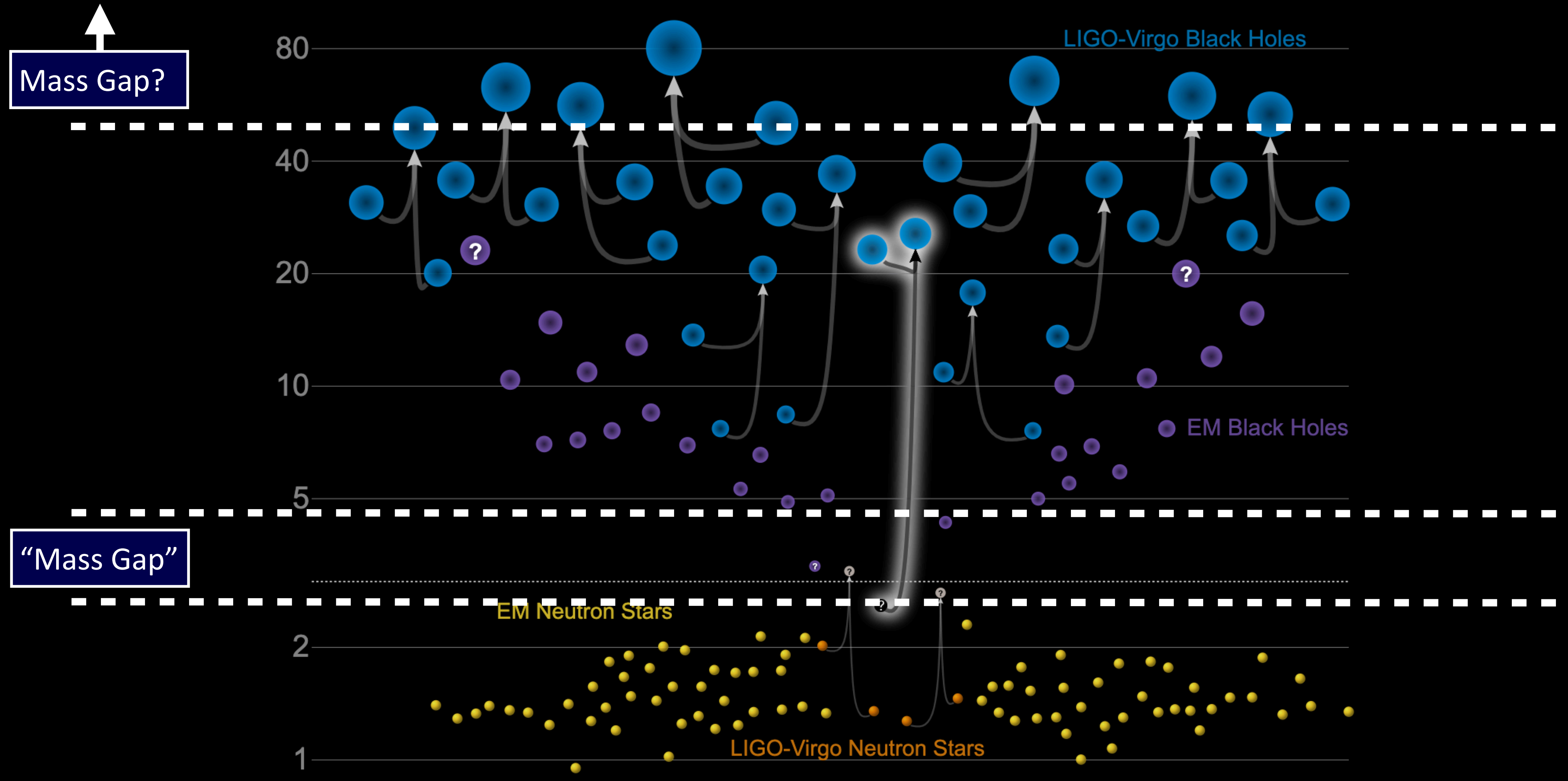

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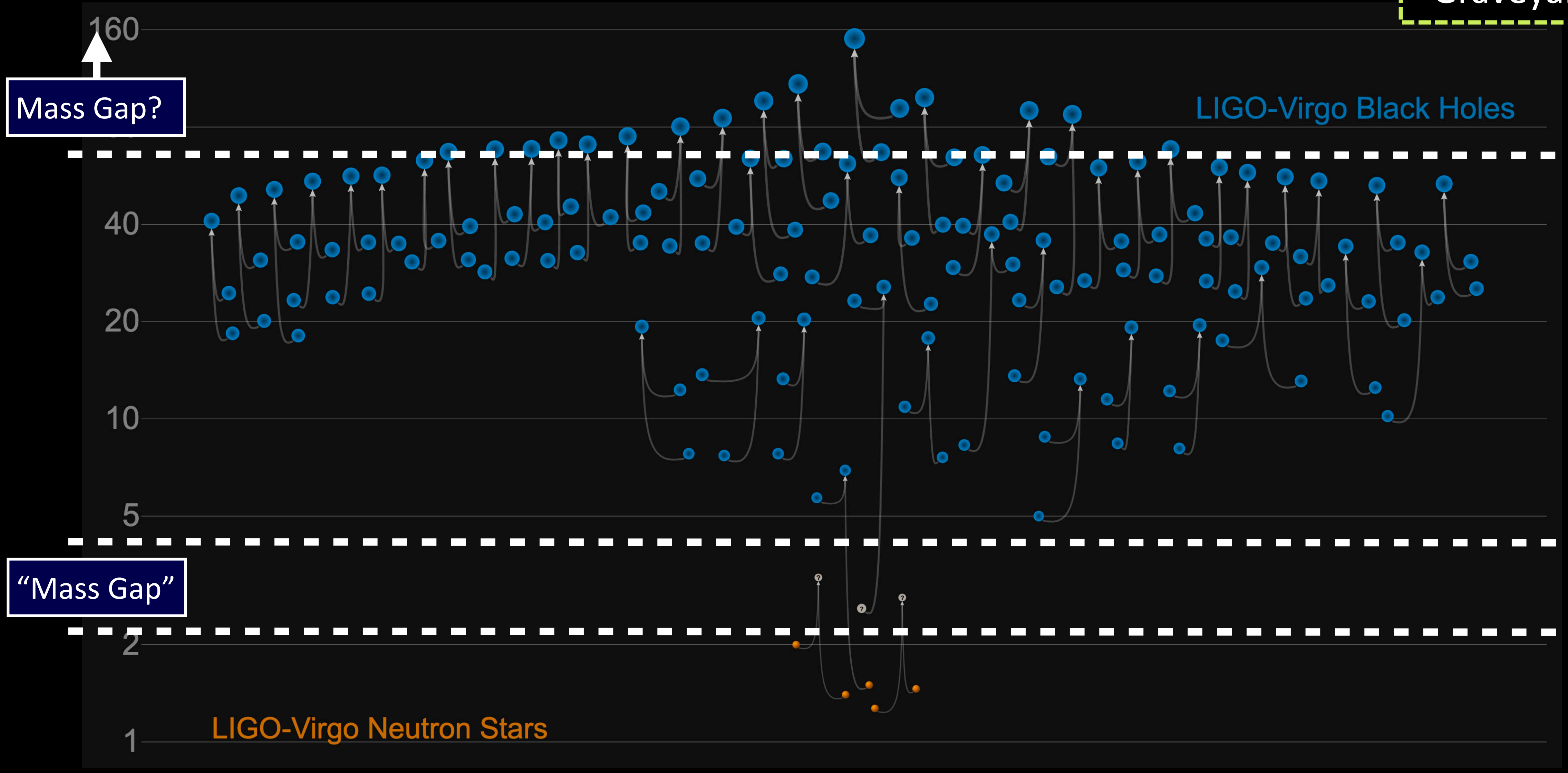
Binary mergers in LIGO/Virgo O3a

“The Stellar Graveyard”



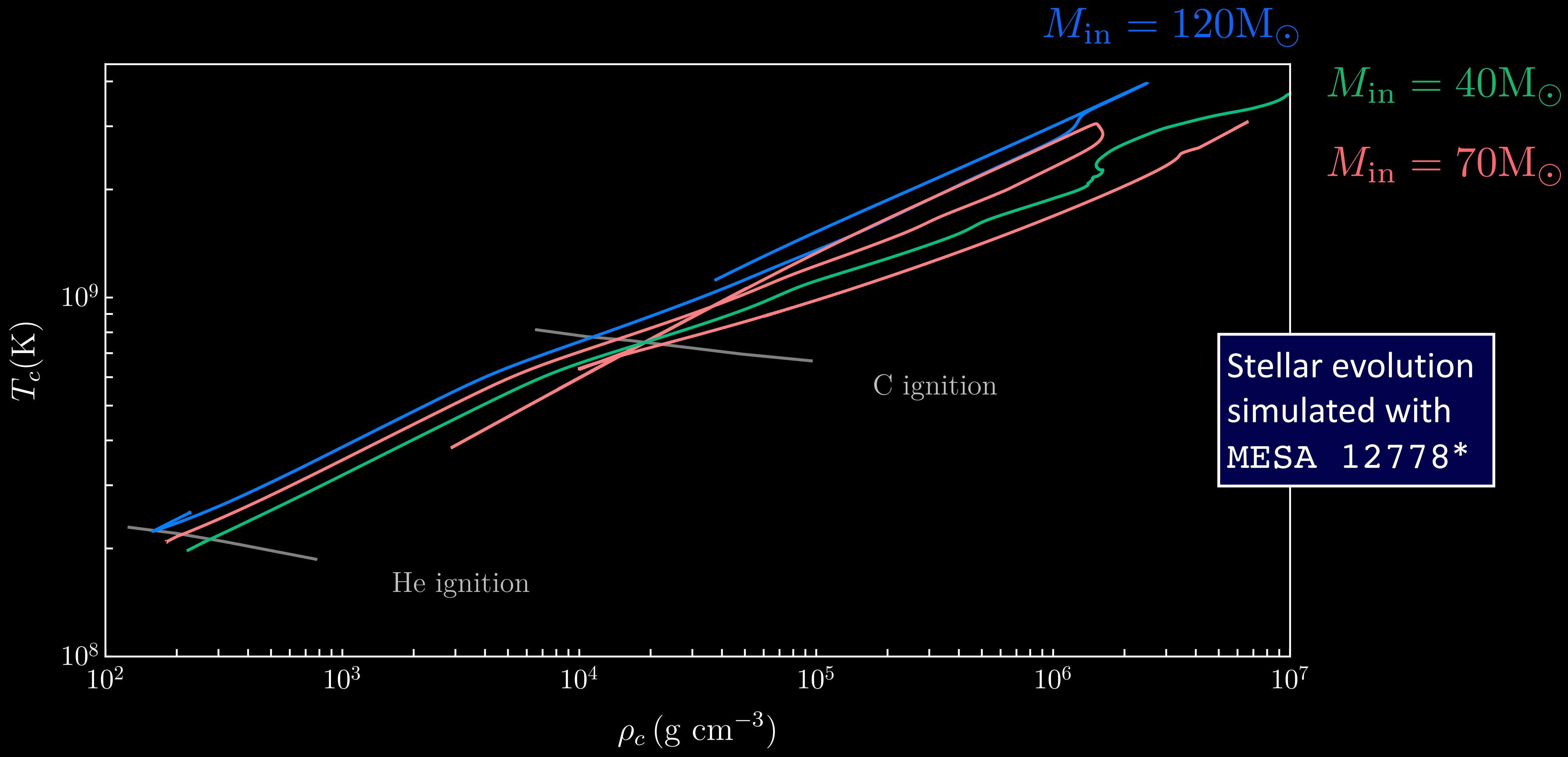
Adapted from LIGO-Virgo, Frank Elavsky, Aaron Geller

What populates the stellar graveyard?

- In the LIGO/Virgo mass range: remnants of heavy, low-metallicity population-III stars
  - Primarily made of hydrogen (H) and helium (He)
  - Would have existed for $z \gtrsim 6, M \sim 20 - 130\,\mathrm{M}_{\odot}$
  - Have not been directly observed yet (JWST target)

- Collapsed into black holes in core-collapse supernova explosions. *(Or did they?)*
- We study their evolution from the Zero-Age Helium Branch (ZAHB)

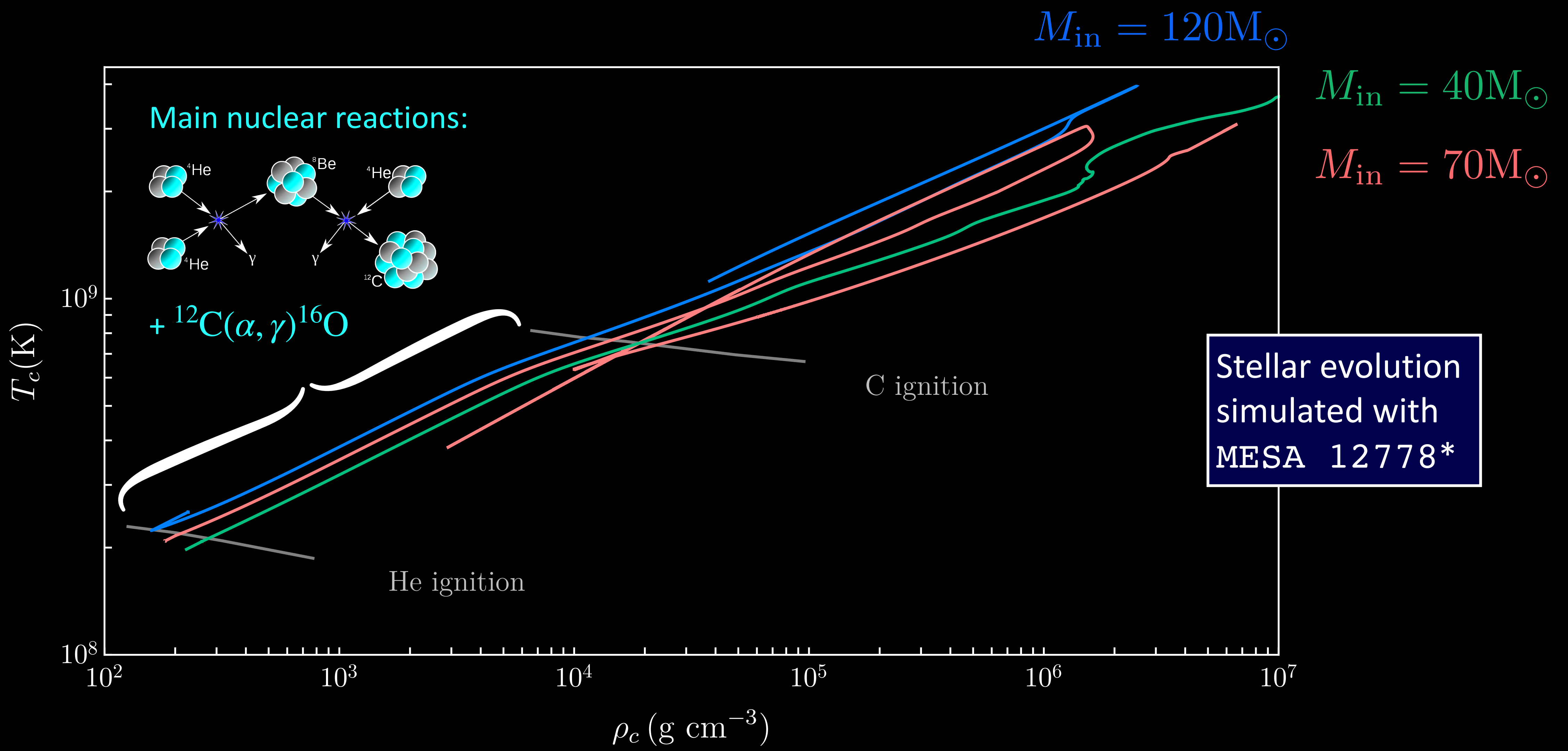
Evolution of old population-III stars



Stellar evolution simulated with `MESA 12778*`

*Paxton et al, arXiv:1710.08424 [astro-ph.SR]

Evolution of old population-III stars



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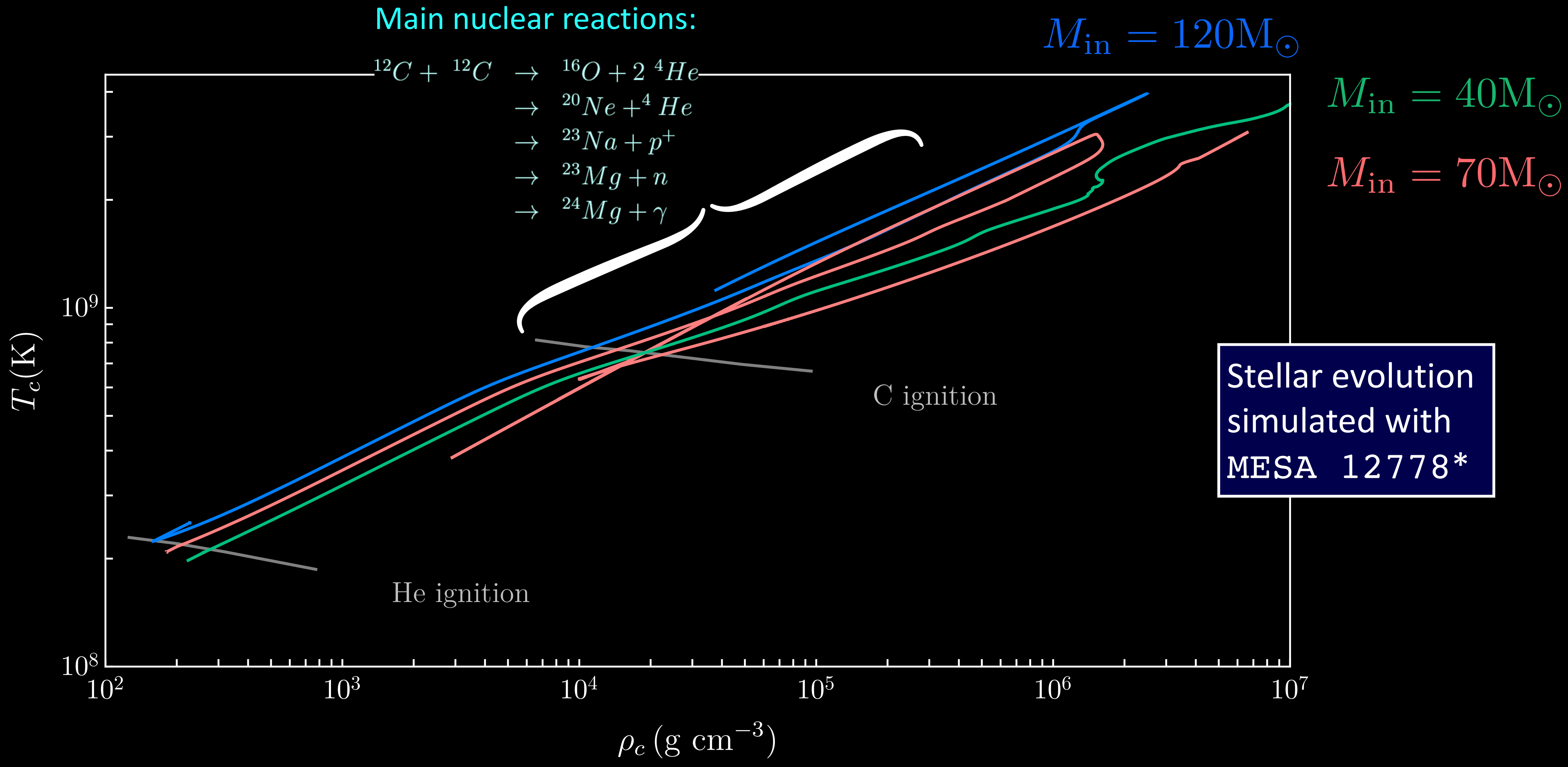

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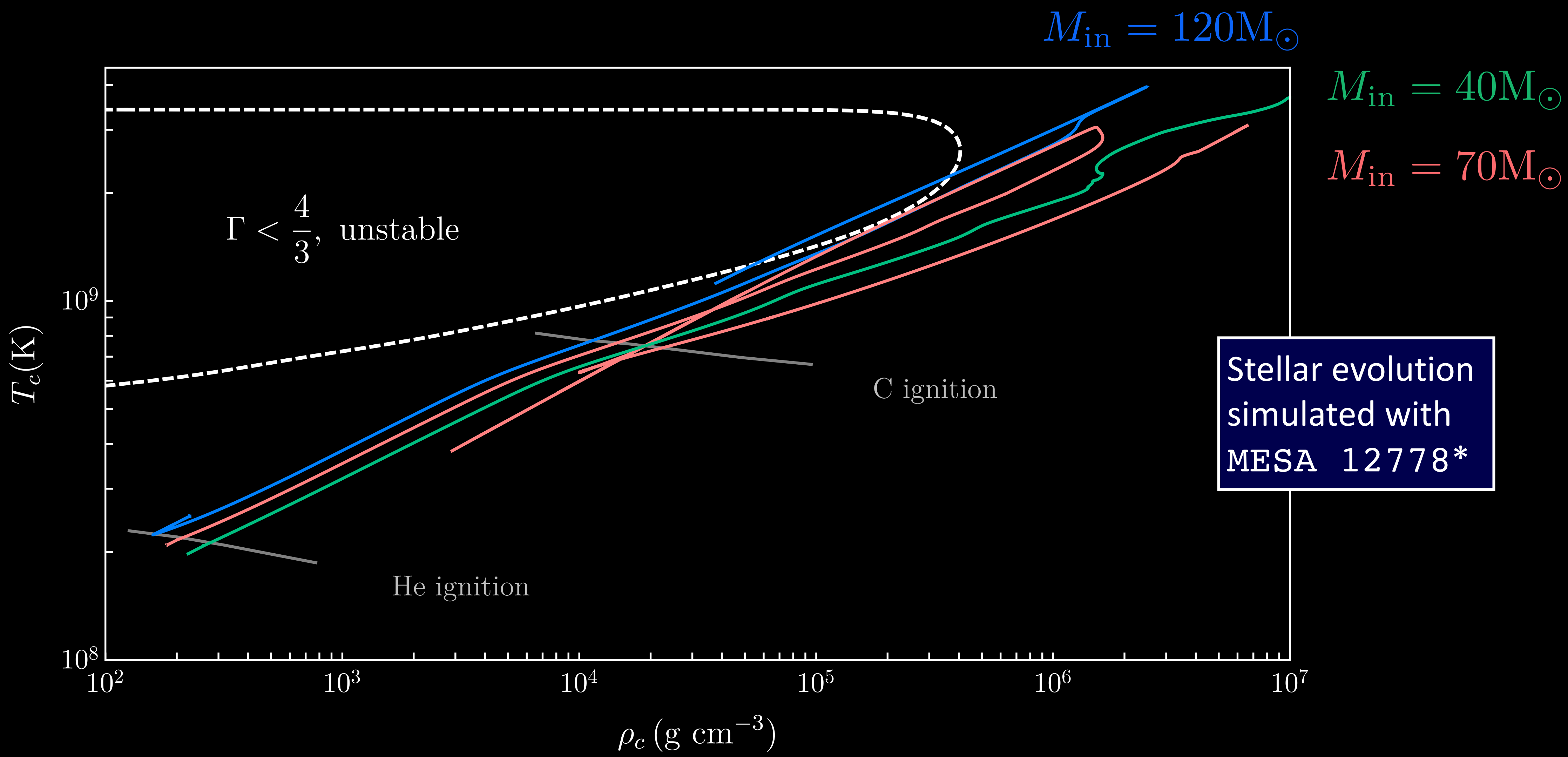


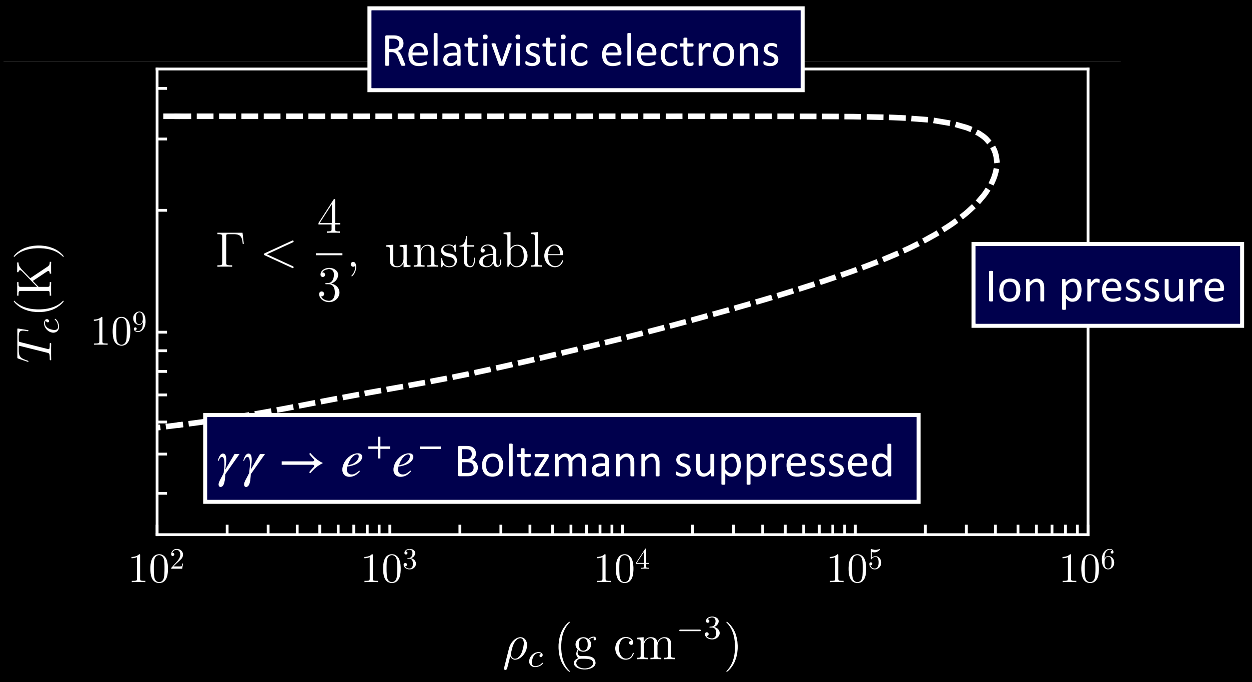
Stellar evolution simulated with `MESA 12778*`

Paxton et al, arXiv:1710.08424 [astro-ph.SR]

Pair-instability

- The high temperatures of the pop-III stars lead to electron-positron pair creation in the thermal plasma via $\gamma\gamma \rightarrow e^+e^-$ $(2m_e \simeq 10^{10}\mathrm{K})$

- Stars supported by radiation pressure $\Gamma = \left(\partial P/\partial \rho\right)_s \approx 4/3$
- Instability occurs for $\Gamma < 4/3$
  - Non-relativistic electrons destabilize the star
  - Rapid thermonuclear burning of ^{16}O follows



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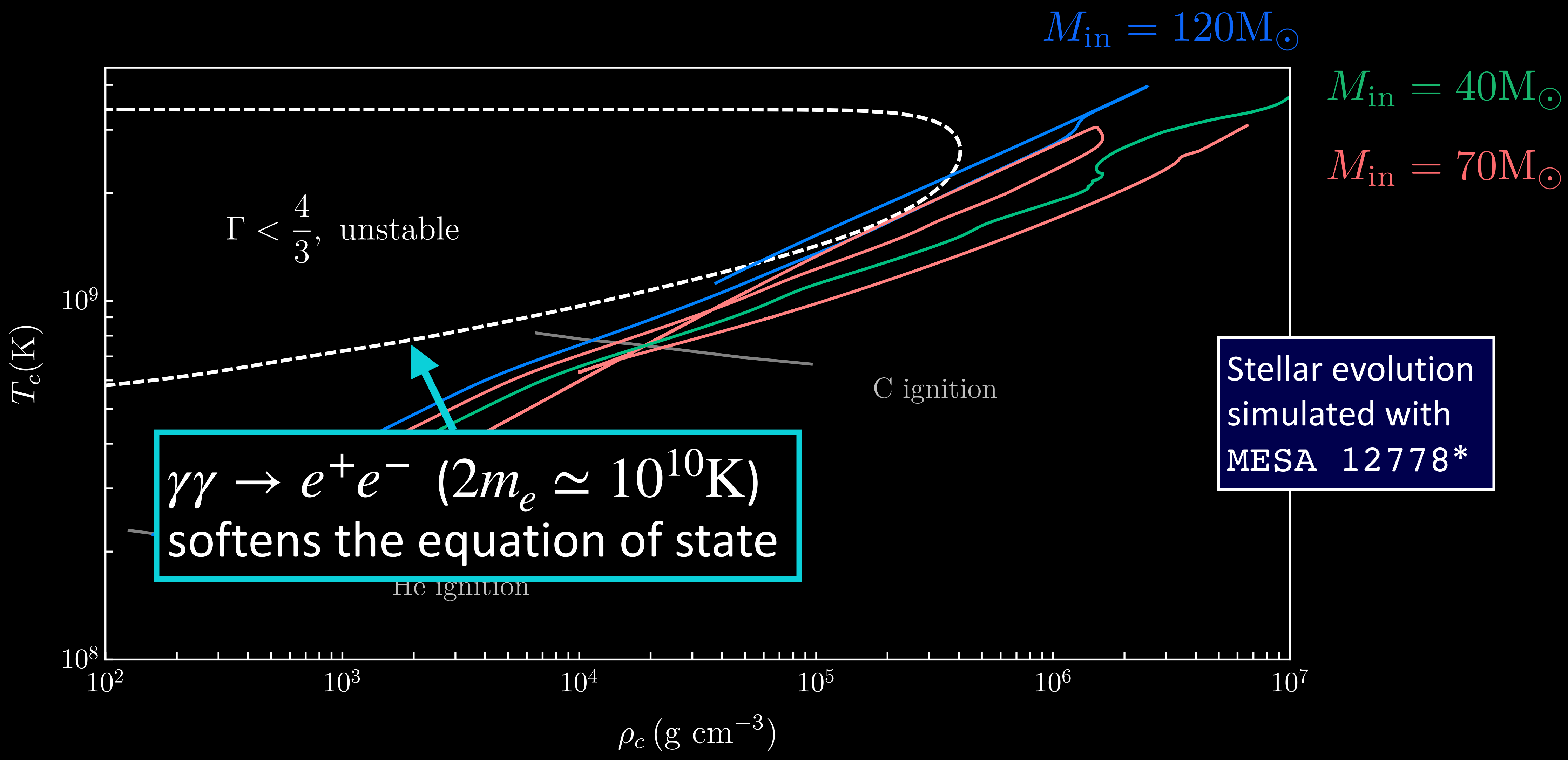

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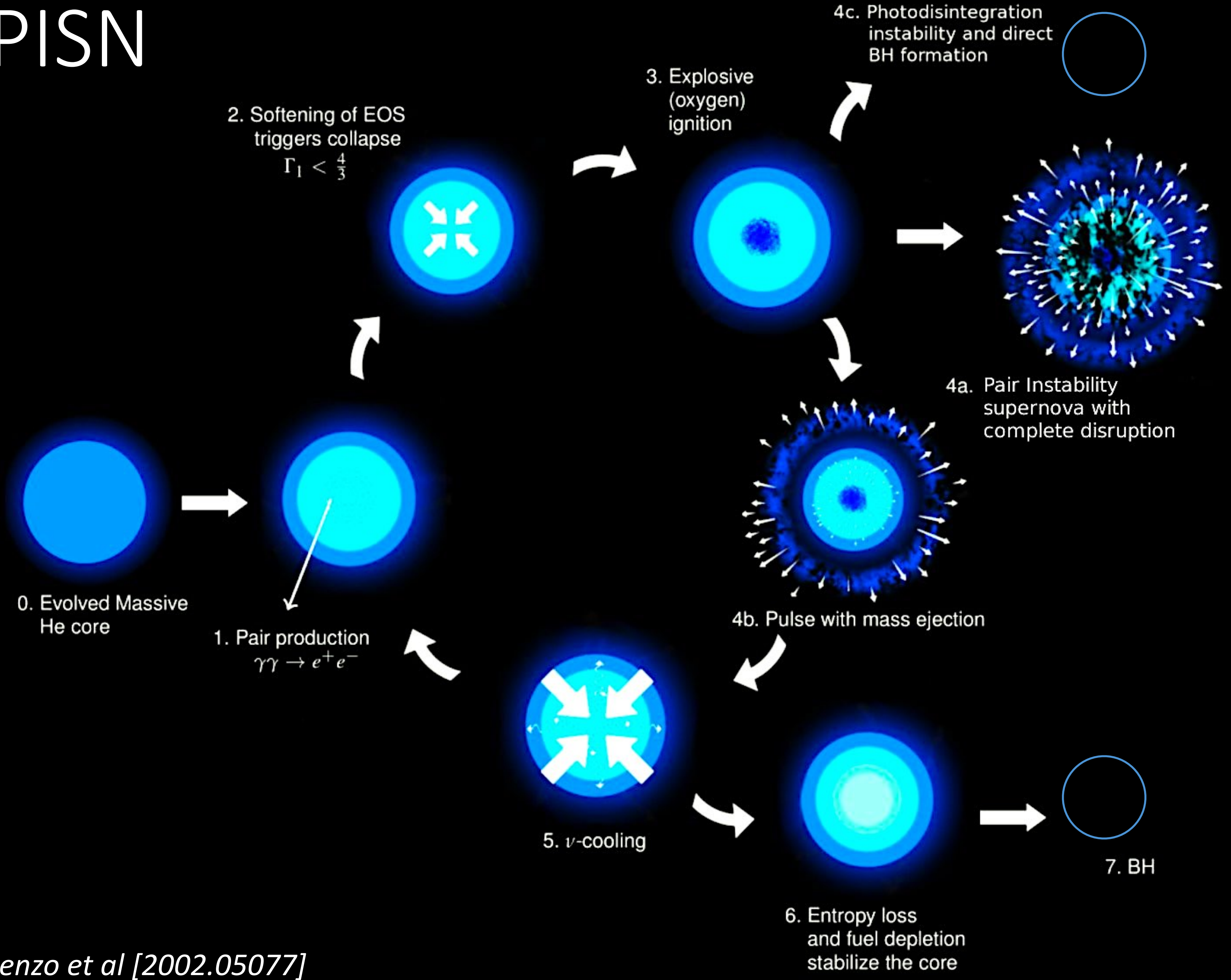
(P)PISN



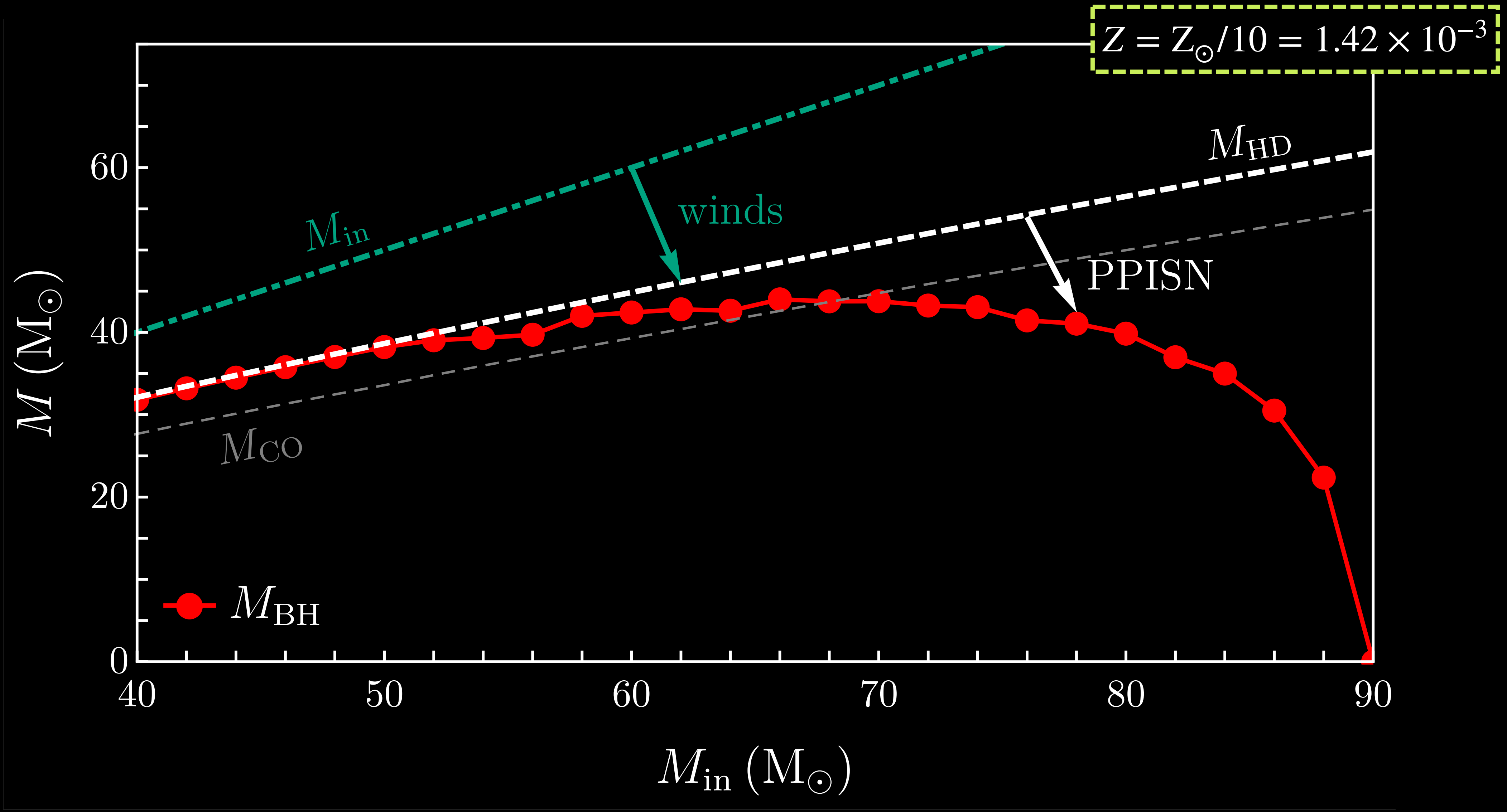
Extremely massive stars ($M_{in} > 200\,M_\odot$)

Very, very massive stars ($M_{in} > 90\,M_\odot$)

Very massive stars ($M_{in} > 50\,M_\odot$)

Adapted from Renzo et al [2002.05077]

Pair-instability and the BHMG



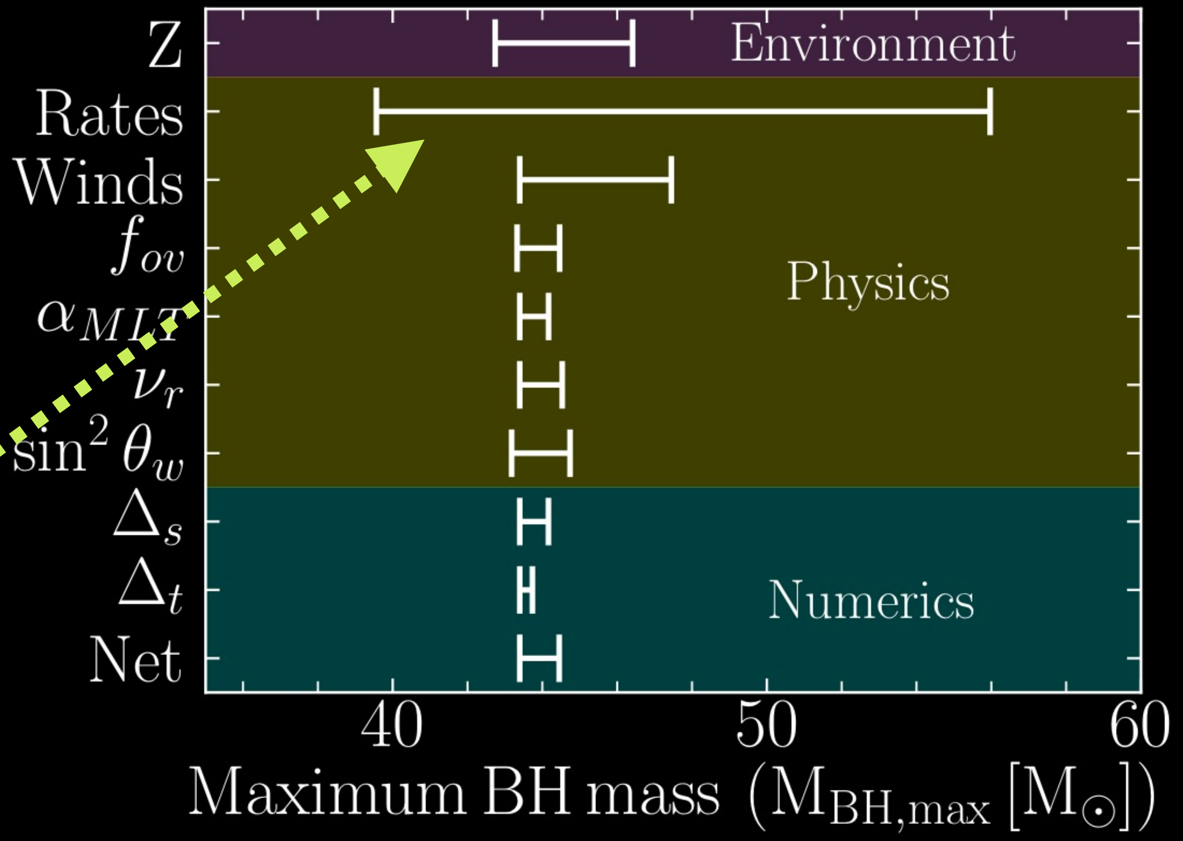
DC, McDermott, Sakstein arXiv:2007.00650 [hep-ph]

Known physics dependence of the BHMG

- Astrophysical + nuclear + numerical uncertainties

- Most important uncertainty: $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ rate
- Using updated deBoer et al rate, BHMG found at $51^{+0}_{-4}\,\mathrm{M}_{\odot}$

deBoer et al arXiv:1709.03144 [hep-ex]
Farmer, Renzo, de Mink, Fishbach, Justham arXiv:2006.06678 [astro-ph.SR]



Farmer, Renzo, de Mink, Marchant, Justham arXiv:1910.12874 [astro-ph.SR]

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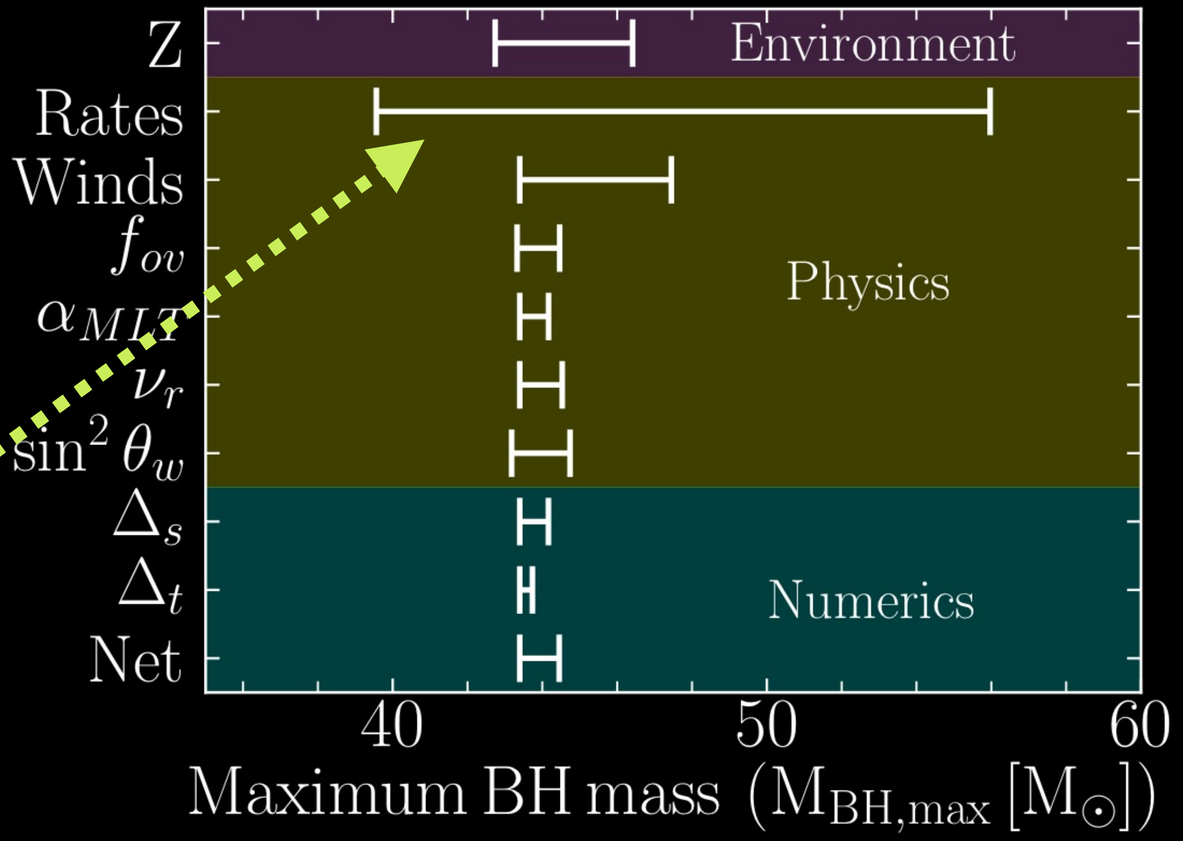
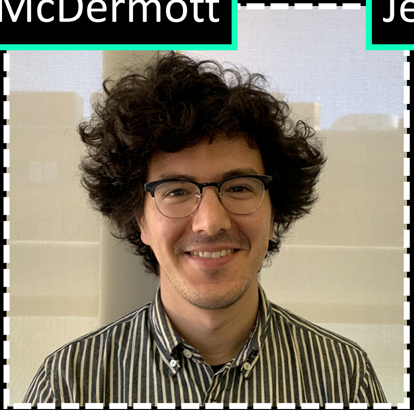


deBoer et al arXiv:1709.03144 [hep-ex]
Farmer, Renzo, de Mink, Fishbach, Justham arXiv:2006.06678 [astro-ph.SR]

But GW190521?!

Farmer, Renzo, de Mink, Marchant, Justham arXiv:1910.12874 [astro-ph.SR]

What about new physics?


Sam McDermott


Jeremy Sakstein


Eric Baxter


Maria Straight

DC, McDermott, Sakstein arXiv:2007.00650 [hep-ph]

DC, McDermott, Sakstein arXiv:2007.07889 [gr-qc]

Sakstein, DC, McDermott, Straight, Baxter arXiv:2009.01213 [gr-qc]

DC, McDermott, Sakstein arXiv:2007.00650 [hep-ph]

DC, McDermott, Sakstein arXiv:2007.07889 [gr-qc]

The BHMG and new physics

- Scenario 1: new, light particles coupled to material in the star introduce new loss channels

- Case studies:
  - the electrophilic axion $\mathscr{L}_{ae} = -ig_{ae}\bar{\psi}_e\gamma_5\psi_e a$ (will also work with $\alpha_{26} \equiv 10^{26} g_{ae}^2/4\pi$ for convenience)*
  - the photophilic axion $\mathscr{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma} a F_{\mu\nu} \widetilde{F}^{\mu\nu}$ (will also define $g_{10} \equiv 10^{10} g_{a\gamma}\,\mathrm{GeV}$)
  - the hidden photon $\mathscr{L}_{A'\gamma} = -\frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu} + \frac{m_{A'}^2}{2} A_\mu A^\mu$ (and define nothing)

*Interesting in light of the XENON1T excess, arXiv:2006.09721 [hep-ex]

DC, McDermott, Sakstein arXiv:2007.00650 [hep-ph]

DC, McDermott, Sakstein arXiv:2007.07889 [gr-qc]

The BHMG and new physics

- Scenario 1: new, light particles coupled to material in the star introduce new loss channels

Extra scenarios: large extra dimensions ($d = 4 + 2$) and neutrino magnetic moment work through essentially the same mechanism

- Case studies:
  - the electrophilic axion $\mathscr{L}_{ae} = -ig_{ae}\bar{\Psi}_e\gamma_5\psi_e a$ (will also work with $\alpha_{26} \equiv 10^{26}g_{ae}^2/4\pi$ for convenience)*
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*Interesting in light of the XENON1T excess, arXiv:2006.09721 [hep-ex]

DC, McDermott, Sakstein arXiv:2007.00650 [hep-ph]

Energy loss due to electrophilic axions

- Semi-Compton scattering, $e + \gamma \to e + a$:

$$\mathcal{Q}_{\rm sC} = \frac{40\,\zeta_6 \alpha_{\rm EM} g_{ae}^2}{\pi^2} \frac{Y_e T^6}{m_N m_e^4} F_{\rm deg} \simeq 33\,\alpha_{26}\, Y_e\, T_8^6\, F_{\rm deg}\, \frac{\rm erg}{\rm g \cdot s} \qquad \left(T_8 \equiv \frac{T}{10^8 {\rm K}} \right)$$

$$F_{\rm deg} = \frac{2}{n_e} \int \frac{d^3\mathbf{p}}{(2\pi)^3} f_{e^-}(1 - f_{e^-}),$$ where f_{e^-} is the Fermi-Dirac distribution

- Bremsstrahlung, $e + (Z, A) \to e + (Z, A) + a$:

$$\mathcal{Q}_{b,\rm ND} = \frac{32}{45} \frac{\alpha_{\rm EM}^2 g_{ae}^2 \rho T^{5/2}}{\sqrt{\frac{\pi^3}{2}} m_N^2 m_e^{7/2}} F_{b,\rm ND} \simeq 582\,\alpha_{26}\,\rho_6\, T_8^{5/2}\, F_{b,\rm ND}\, \frac{\rm erg}{\rm g \cdot s} \qquad \left(\rho_6 \equiv \frac{\rho}{10^6 {\rm g\,cm^{-3}}} \right)$$

$$\mathcal{Q}_{b,\rm D} = \frac{\pi}{60} \frac{Z^2}{A} \frac{\alpha_{\rm EM}^2 g_{ae}^2 T^4}{m_N m_e^2} F_{b,\rm D} \simeq 10.8\,\alpha_{26}\, T_8^4\, F_{b,\rm D}\, \frac{\rm erg}{\rm g \cdot s}$$

DC, McDermott, Sakstein arXiv:2007.00650 [hep-ph]

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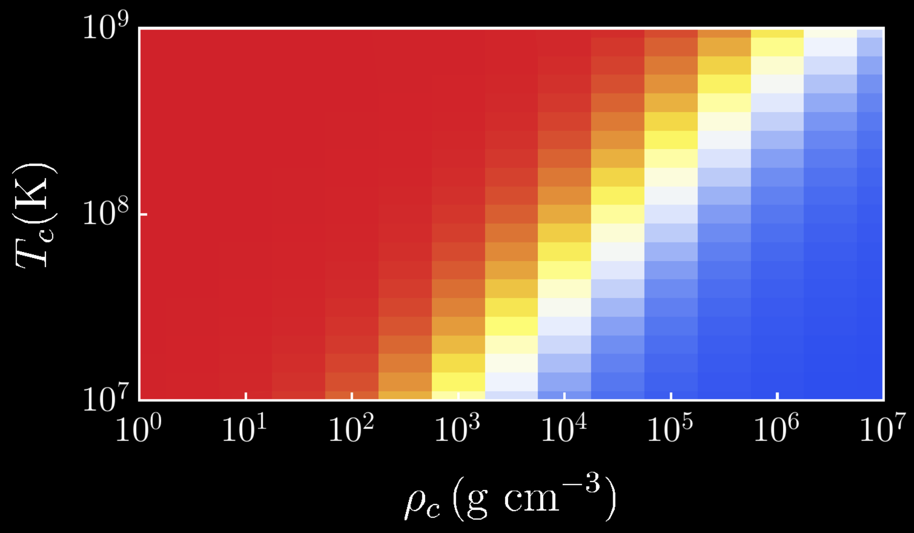
$0 < F_{\rm deg} < 1$



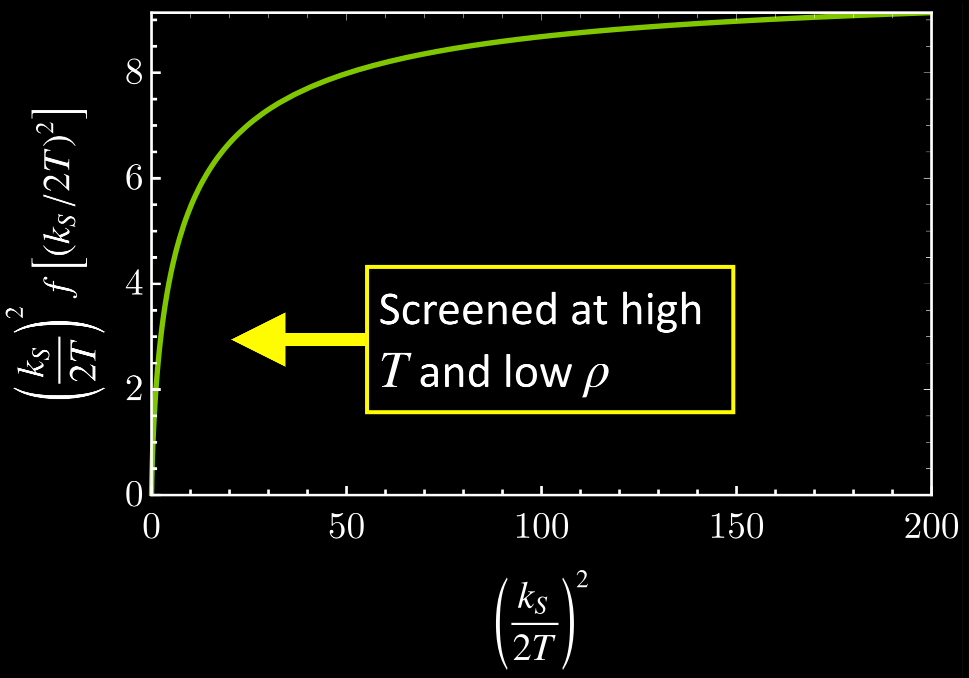
Semi-Compton emission dominates throughout the Helium burning phase

Energy loss due to photophilic axions

- Primakov effect $(Z, A) + \gamma \to (Z, A) + a$

$$\mathcal{Q}_{a\gamma} = \frac{g_{a\gamma}^2 T^7}{4\pi^2\rho}\left(\frac{k_S}{2T}\right)^2 f[(k_S/2T)^2] \simeq 283.16\frac{\text{erg}}{\text{g}\cdot\text{s}} g_{10}^2 T_8^7 \rho_3^{-1}\left(\frac{k_S}{2T}\right)^2 f[(k_S/2T)^2]$$

- With Debye momentum
  - $$\left(\frac{k_S}{2T}\right)^2 = 0.166\frac{\rho_3}{T_8^3}\sum_j Y_j Z_j^2$$



DC, McDermott, Sakstein arXiv:2007.07889 [gr-qc]

DC, McDermott, Sakstein arXiv:2007.07889 [gr-qc]

Energy loss due to hidden photons

- Plasma production, dominated by longitudinal modes (in a non-relativistic plasma)

$$\mathcal{Q}_{A'} = \frac{\epsilon^2 m_{A'}^2}{4\pi\rho}\frac{\omega_p^3}{e^{\omega_p/T}-1} \simeq \frac{\epsilon^2 m_{A'}^2}{4\pi}\frac{\omega_p^2 T}{\rho} \simeq 1.8\times 10^3 \frac{\text{erg}}{\text{g}\cdot\text{s}}\frac{Z}{A}T_8\left(\frac{\epsilon}{10^{-7}}\frac{m_{A'}}{\text{meV}}\right)^2$$

In the limit $\omega_p \ll T$

- Where photons have plasma mass $\omega_p \simeq \sqrt{\frac{4\pi\alpha_{\text{EM}} n_e}{m_e}} \simeq 654\text{eV}\sqrt{\frac{Z}{A}\rho_3}$

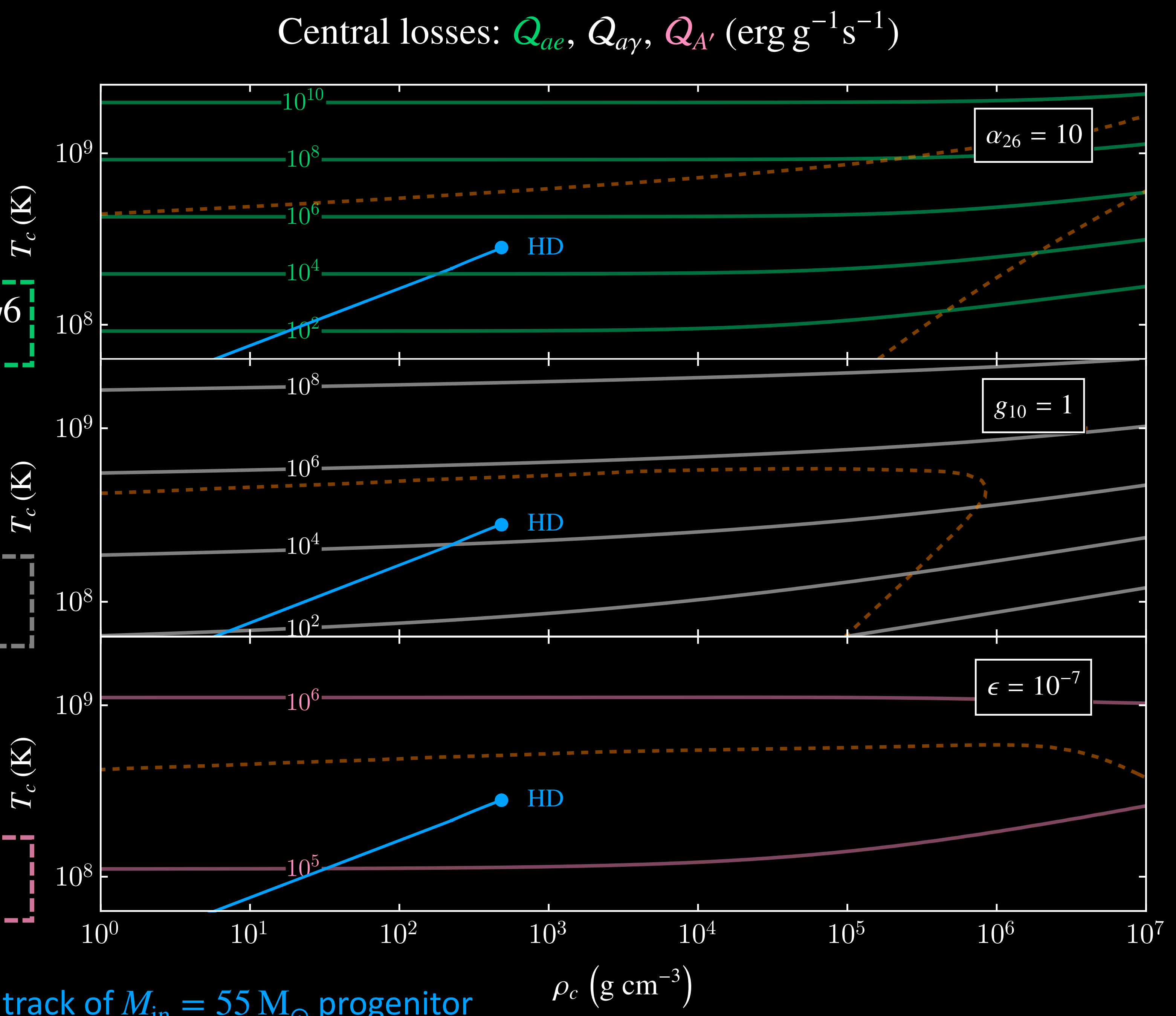
DC, McDermott, Sakstein arXiv:2007.07889 [gr-qc]

Loss rates

Electrophilic axion: $Q_{ae} \propto T^6$

Photophilic axion: $Q_{a\gamma} \propto T^4$

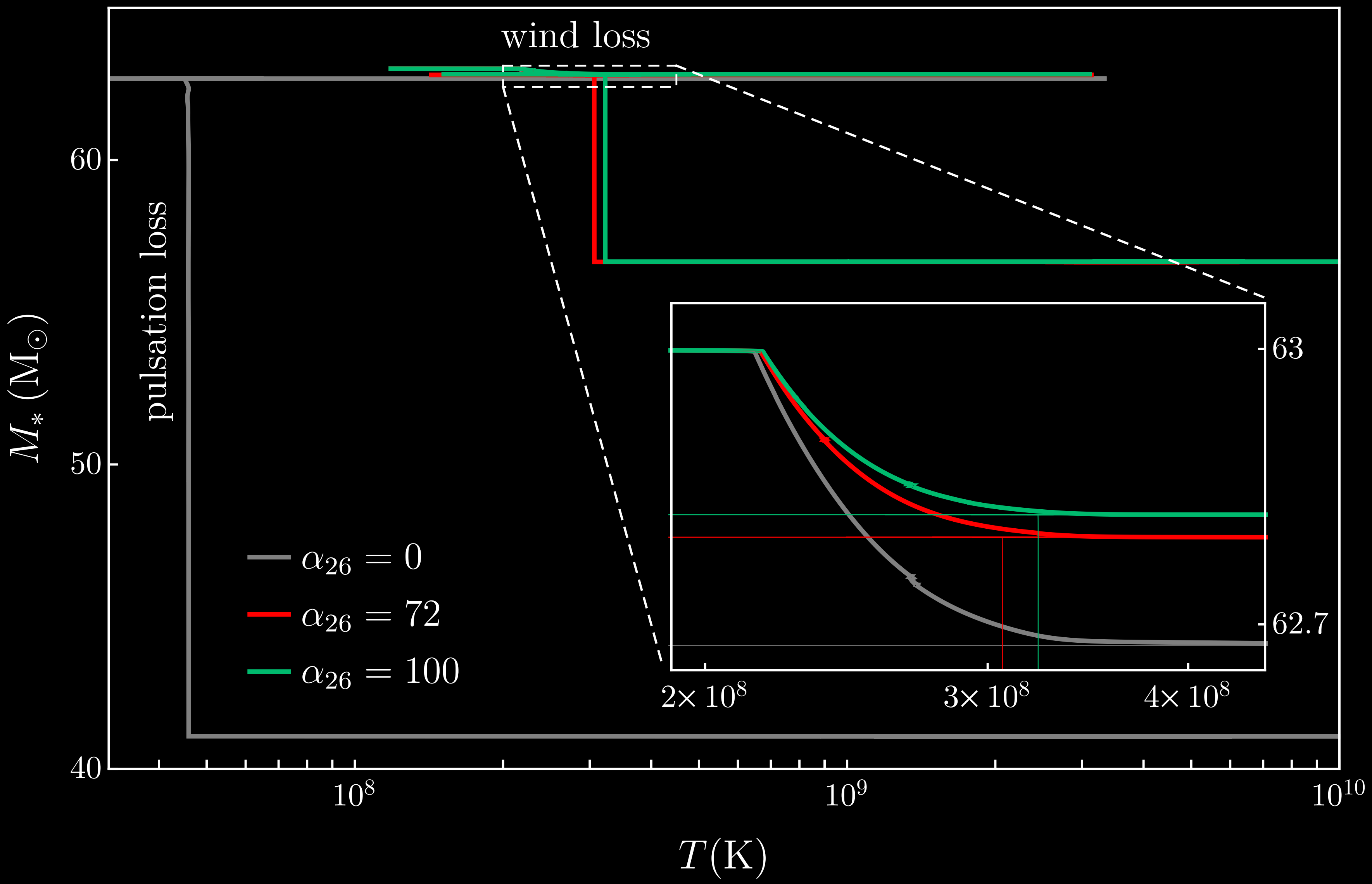
Hidden photon: $Q_{A'} \propto T$



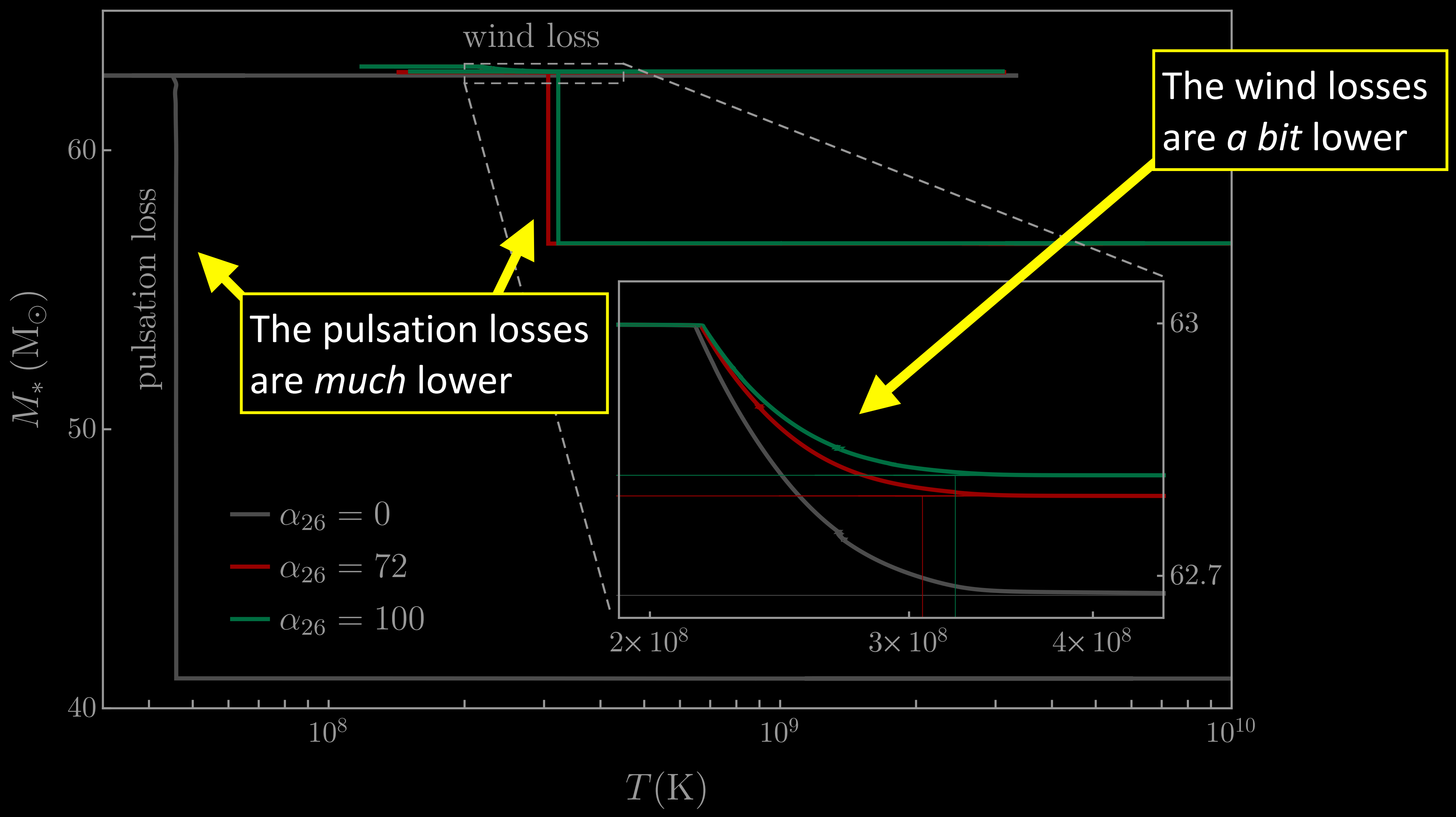
Example track of $M_{\rm in} = 55\,\mathrm{M}_\odot$ progenitor

DC, McDermott, Sakstein arXiv:2007.07889 [gr-qc]

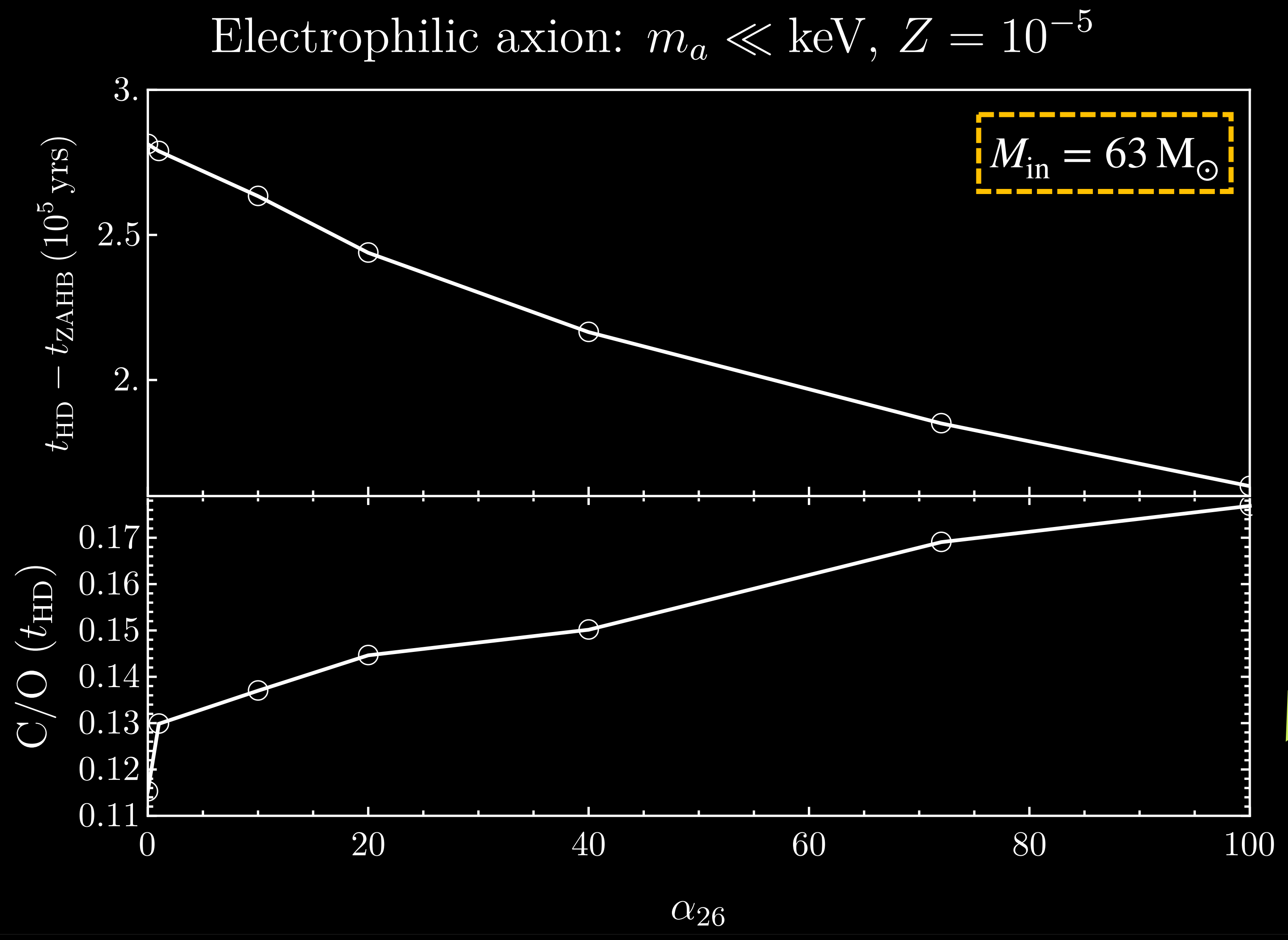
Implications of enhanced losses



Implications of enhanced losses



What does the extra energy loss do?



Greater energy losses lead to *shorter He-burning phases*

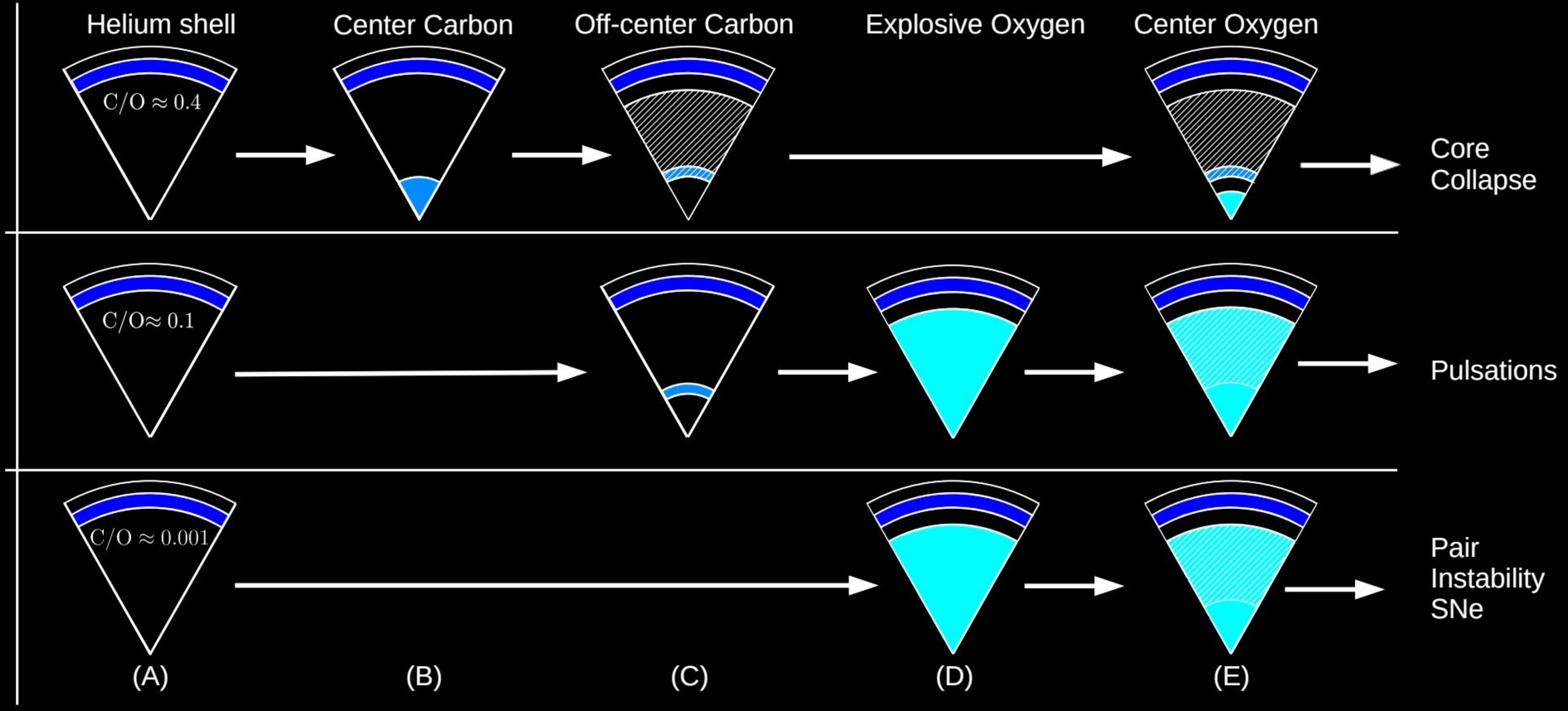
Extra dissipation scales linearly with α_{26}

Less time for $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$: *C/O is larger* at the time of helium depletion (HD)

The BHMG and new physics

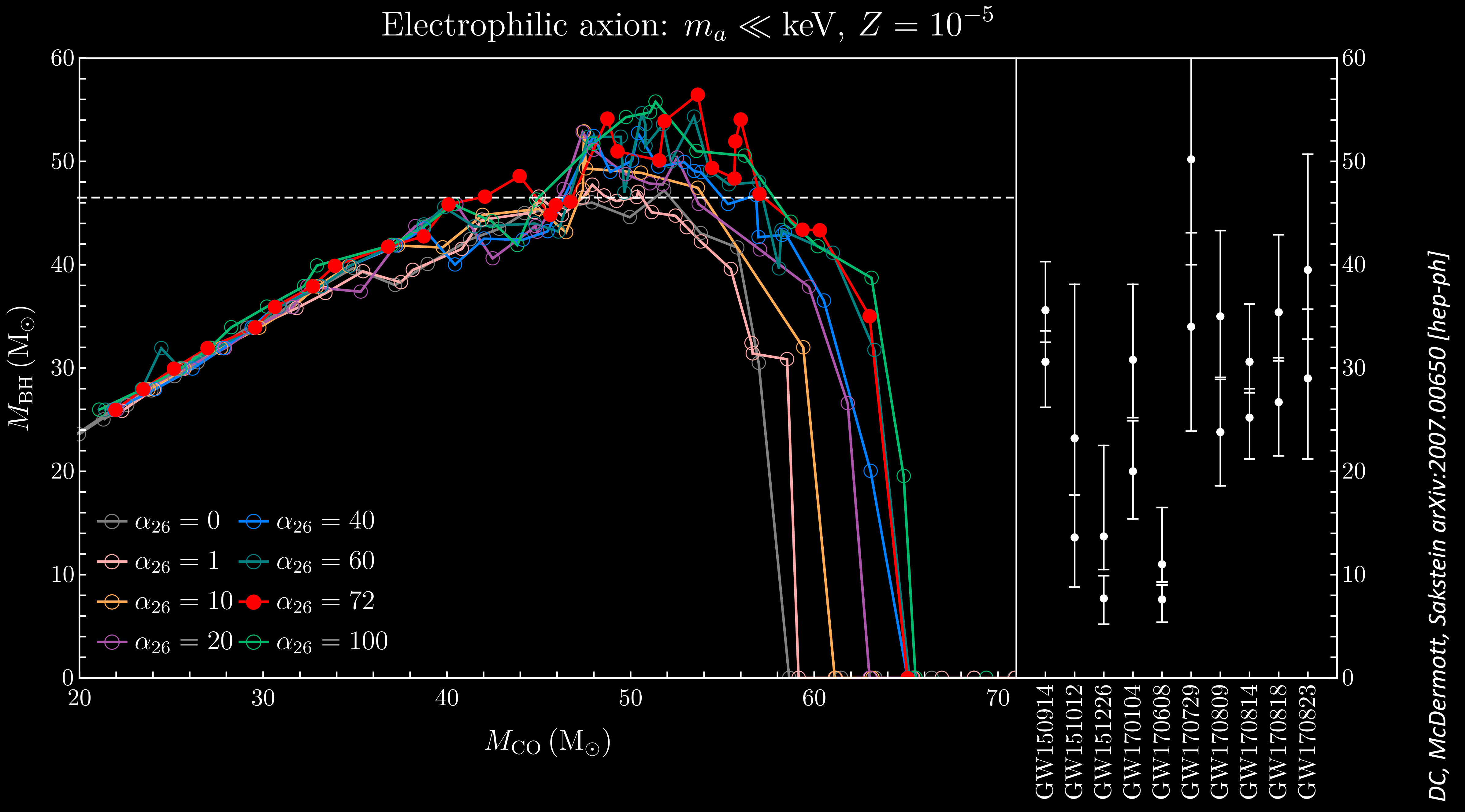
Helium burning
Carbon burning
Oxygen burning

Enhanced losses, larger C/O at HD →

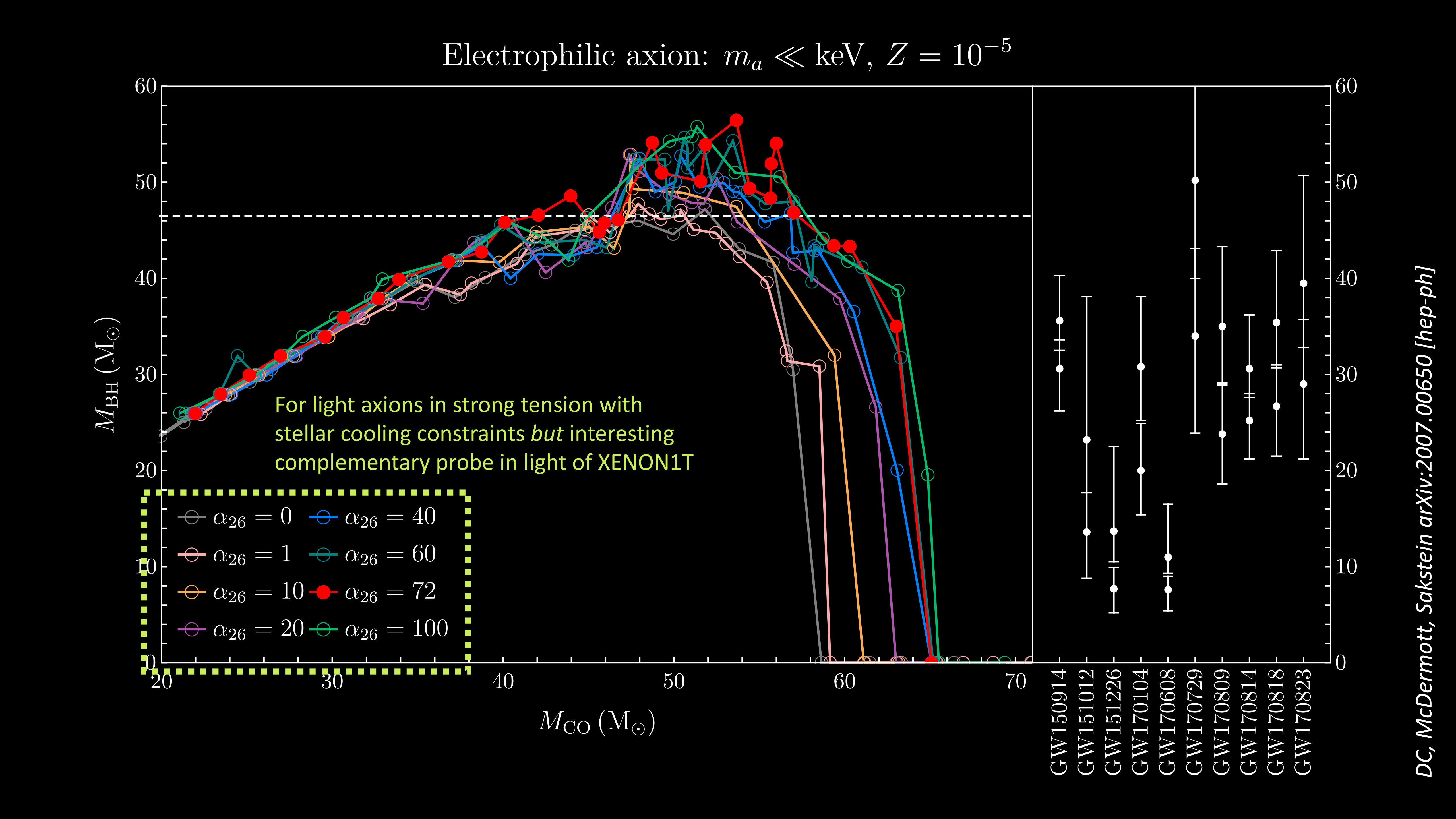


Enhanced losses → greater progenitors collapse → larger black holes

Adapted from Farmer, Renzo, de Mink, Fishbach, Justham [2006.06678]



Electrophilic axion: $m_a \ll$ keV, $Z = 10^{-5}$
$M_{\rm BH}$ ($M_\odot$)
$M_{\rm CO}$ ($M_\odot$)
$\alpha_{26} = 0$
$\alpha_{26} = 1$
$\alpha_{26} = 10$
$\alpha_{26} = 20$
$\alpha_{26} = 40$
$\alpha_{26} = 60$
$\alpha_{26} = 72$
$\alpha_{26} = 100$
GW150914
GW151012
GW151226
GW170104
GW170608
GW170729
GW170809
GW170814
GW170818
GW170823
DC, McDermott, Sakstein arXiv:2007.00650 [hep-ph]



Electrophilic axion: $m_a \ll$ keV, $Z = 10^{-5}$
For light axions in strong tension with stellar cooling constraints *but* interesting complementary probe in light of XENON1T
$M_{\rm BH}$ ($M_\odot$)
$M_{\rm CO}$ ($M_\odot$)
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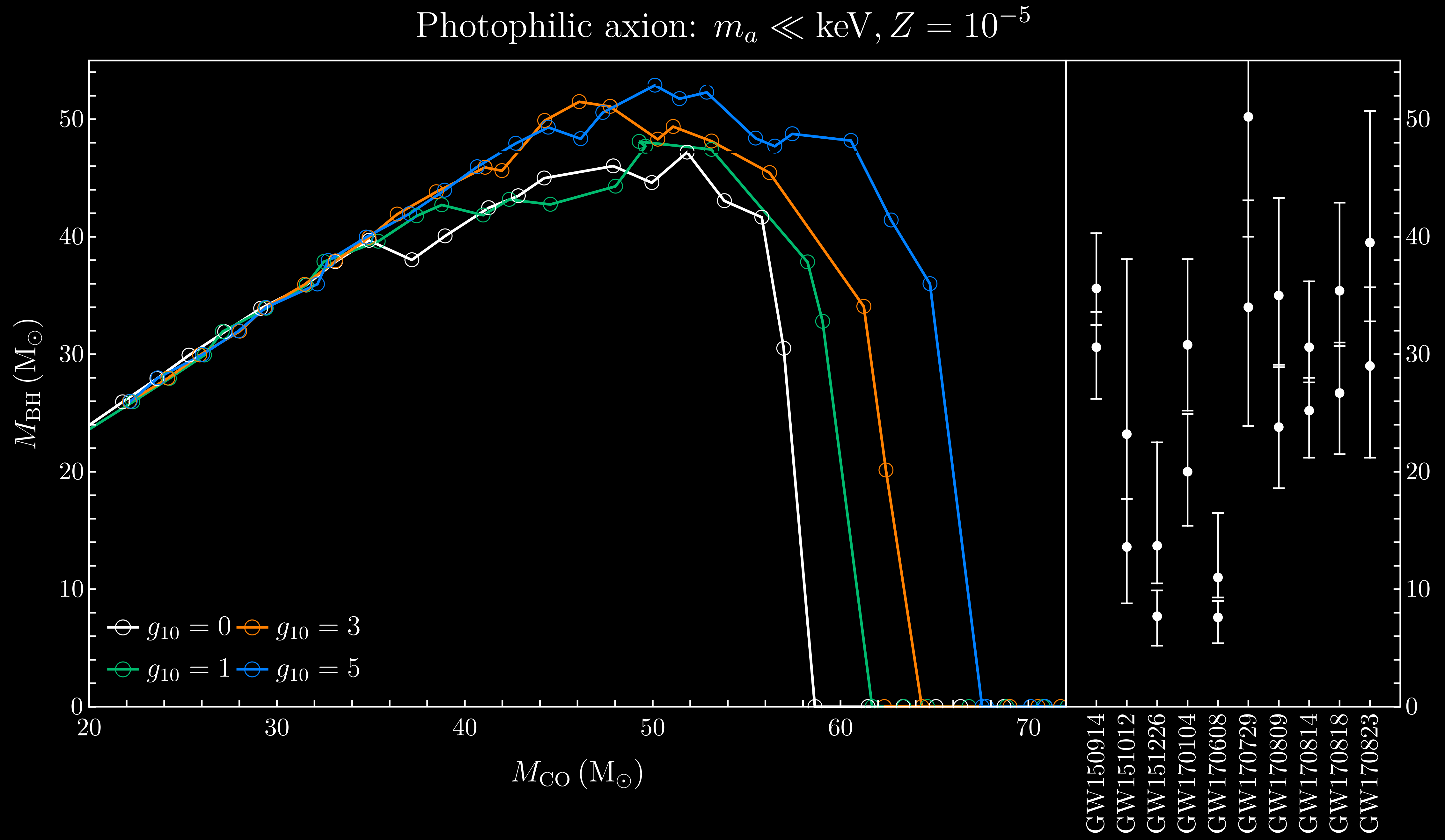

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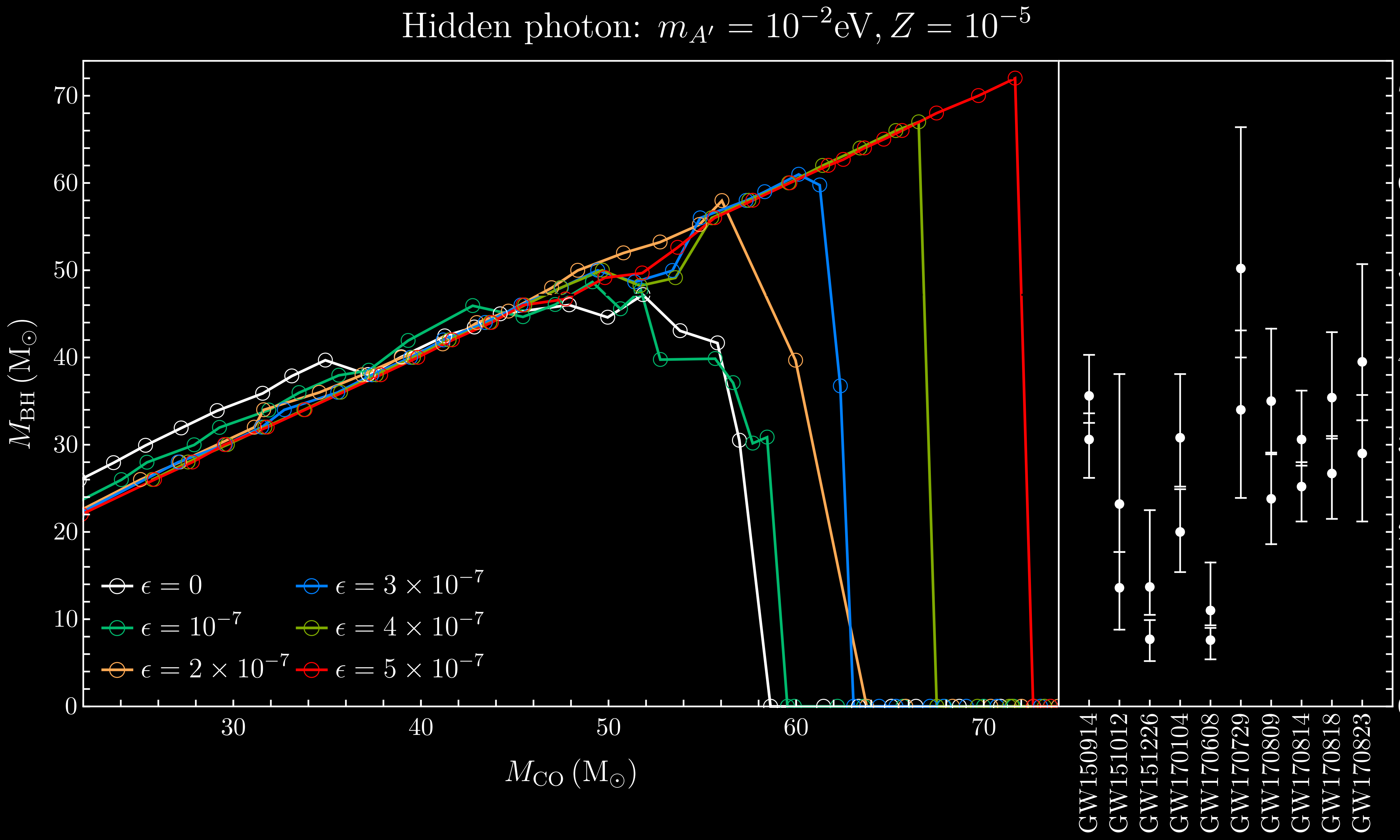

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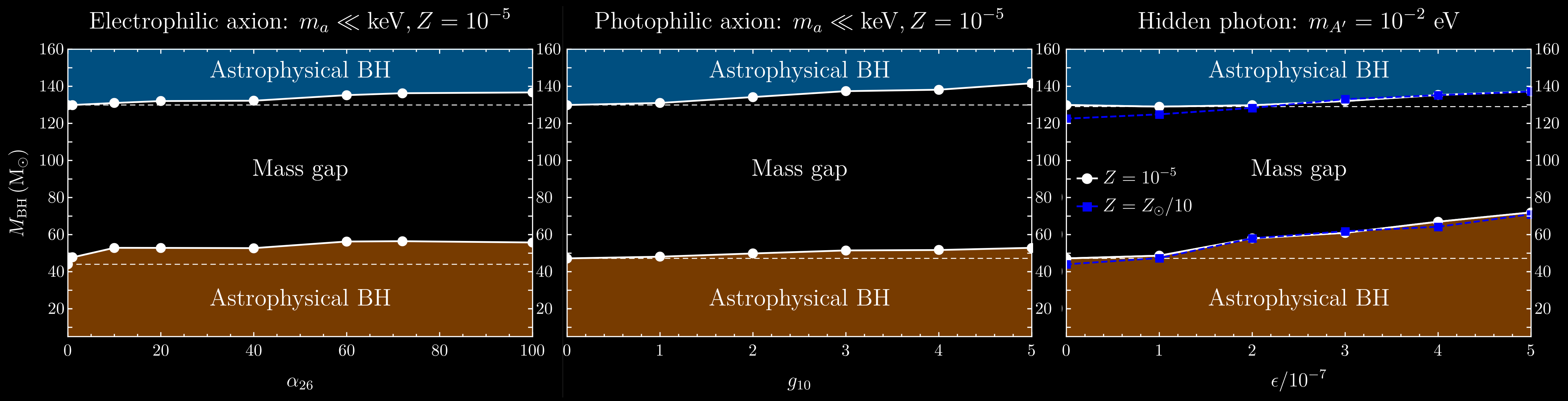
New physics and the black hole mass gap



$\mathcal{Q}_{ae} \propto T^6$

$\mathcal{Q}_{a\gamma} \propto T^4$

$\mathcal{Q}_{A'} \propto T$

Potentially large shifts of the mass gap!

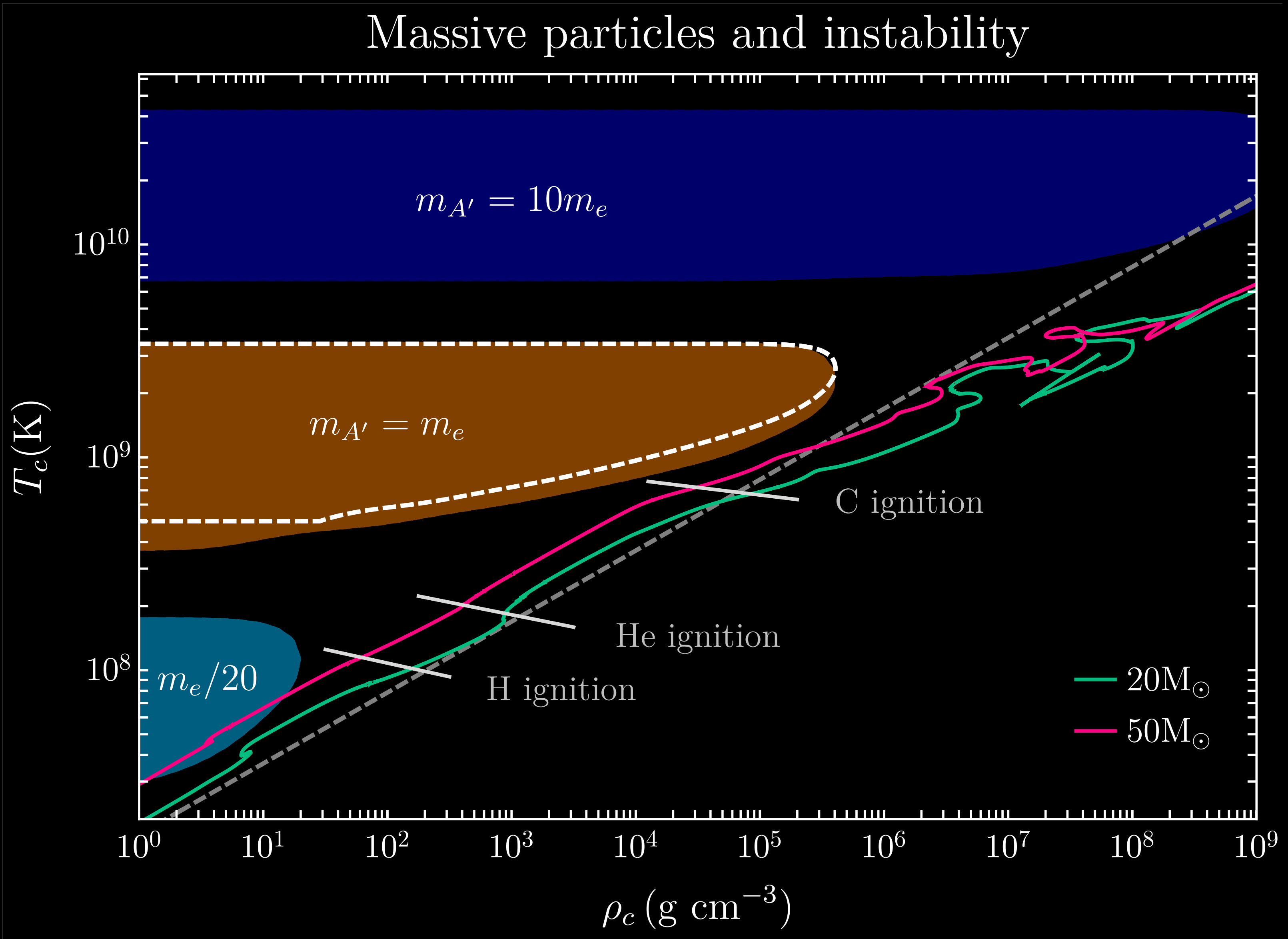
DC, McDermott, Sakstein arXiv:2007.07889 [gr-qc]

Heavier degrees of freedom?

Heavier degrees of freedom may instead be thermalized in the core

Then, they may give rise to an instability in the same way that electron-positron pairs do

Equilibration time (vector):
$t_{A'} \simeq \Gamma_{A'}^{-1} \simeq \left(\epsilon^2 \sigma_T n_e e^{-m_{A'}/T_c}\right)^{-1}$
so for $\epsilon = 3 \times 10^{-12}$, we find $t_{A'} \simeq 10^5$ years, a timescale similar to the lifetime of helium burning



DC, McDermott, Sakstein arXiv:2007.07889 [gr-qc]

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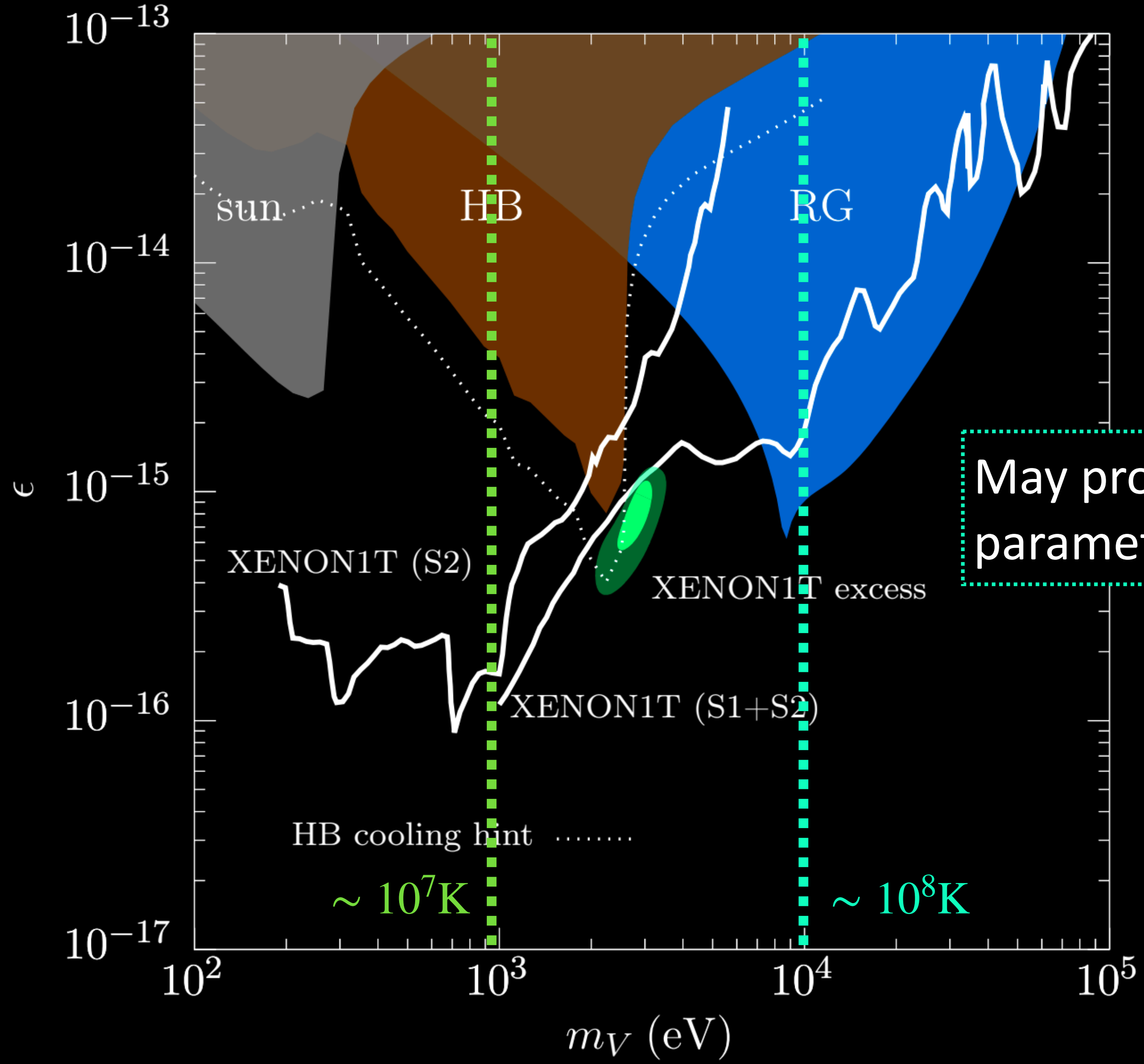


May probe this parameter space

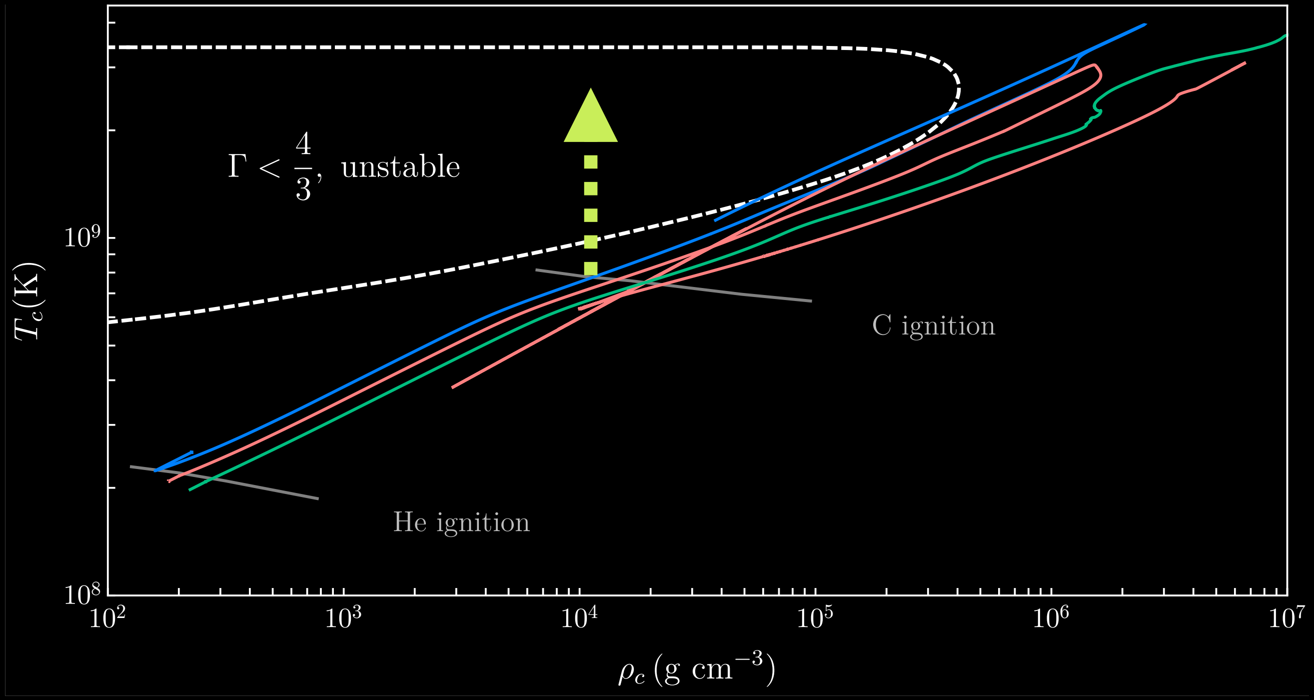
Adapted from Ann, Pospelov, Pradler, Ritz arXiv:2006.13929 [hep-ph]

The BHMG and new physics

Sakstein, DC, McDermott, Straight, Baxter arXiv:2009.01213 [gr-qc]

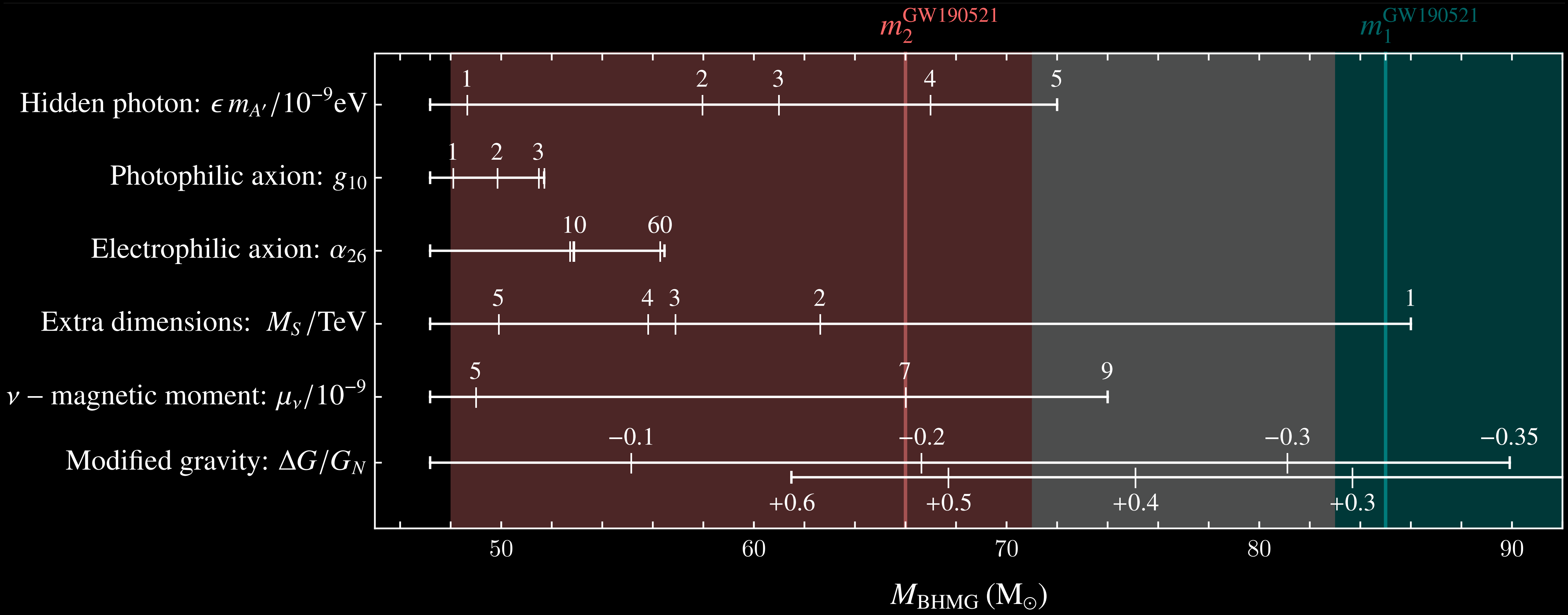
Straight, Sakstein, Baxter, in progress

- Scenario 2: screened modified gravity (MG)
- Increased local strength of gravity → need larger pressure gradient to maintain hydrostatic equilibrium → larger core temperature at fixed density
- Pair instability is exacerbated →Lighter black holes
- Decreased local strength of gravity works in reverse → Heavier black holes



GW190521, the impossible black holes

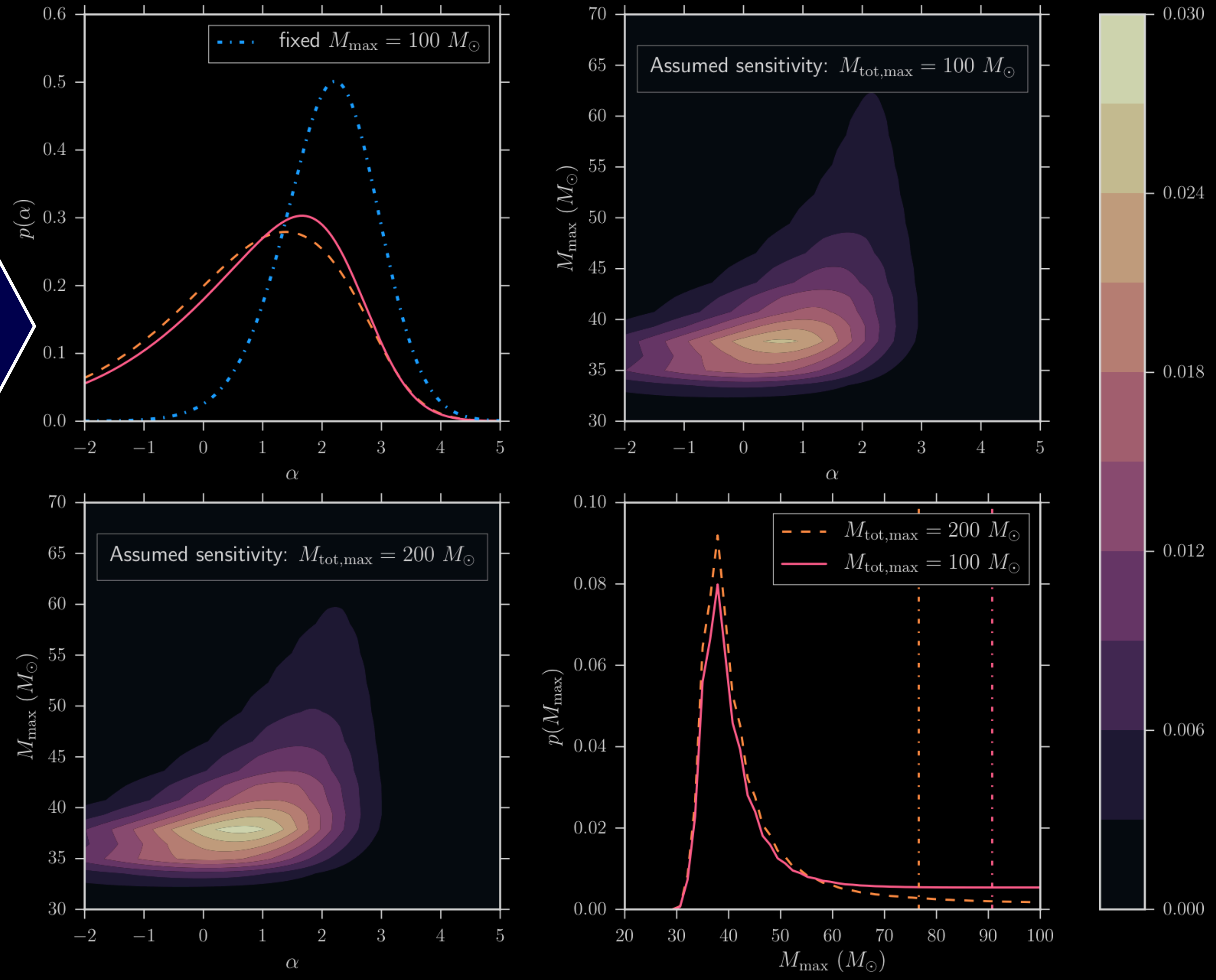
… and Beyond the Standard Model physics



Sakstein, DC, McDermott, Straight, Baxter arXiv:2009.01213 [gr-qc]

Looking ahead…

Posterior PDFs using the first 4 BBH mergers, and assuming a power law mass distribution, $p(m_1\,|\,\alpha) \propto m_1^{-\alpha}$



With the complete O3 data set (and beyond), the field of *black hole population studies* will really take off!

from Fishbach & Holz, arXiv:1709.08584 [astro.ph]

To conclude,

- Gravitational waves offer an exciting new opportunity to study open questions in particle astrophysics and cosmology

- Binary mergers allow for black hole population studies

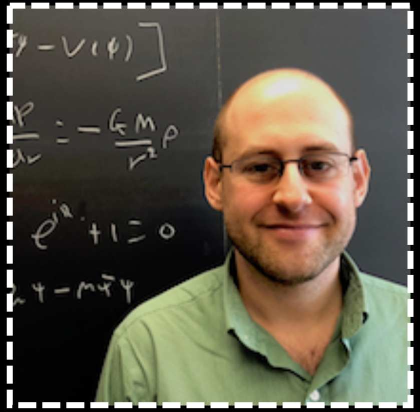
- The black hole mass gap is an exciting probe of new physics, which will come into focus in the next few years

- GW190521 constitutes an intriguing puzzle which could be (partially) explained by BSM physics

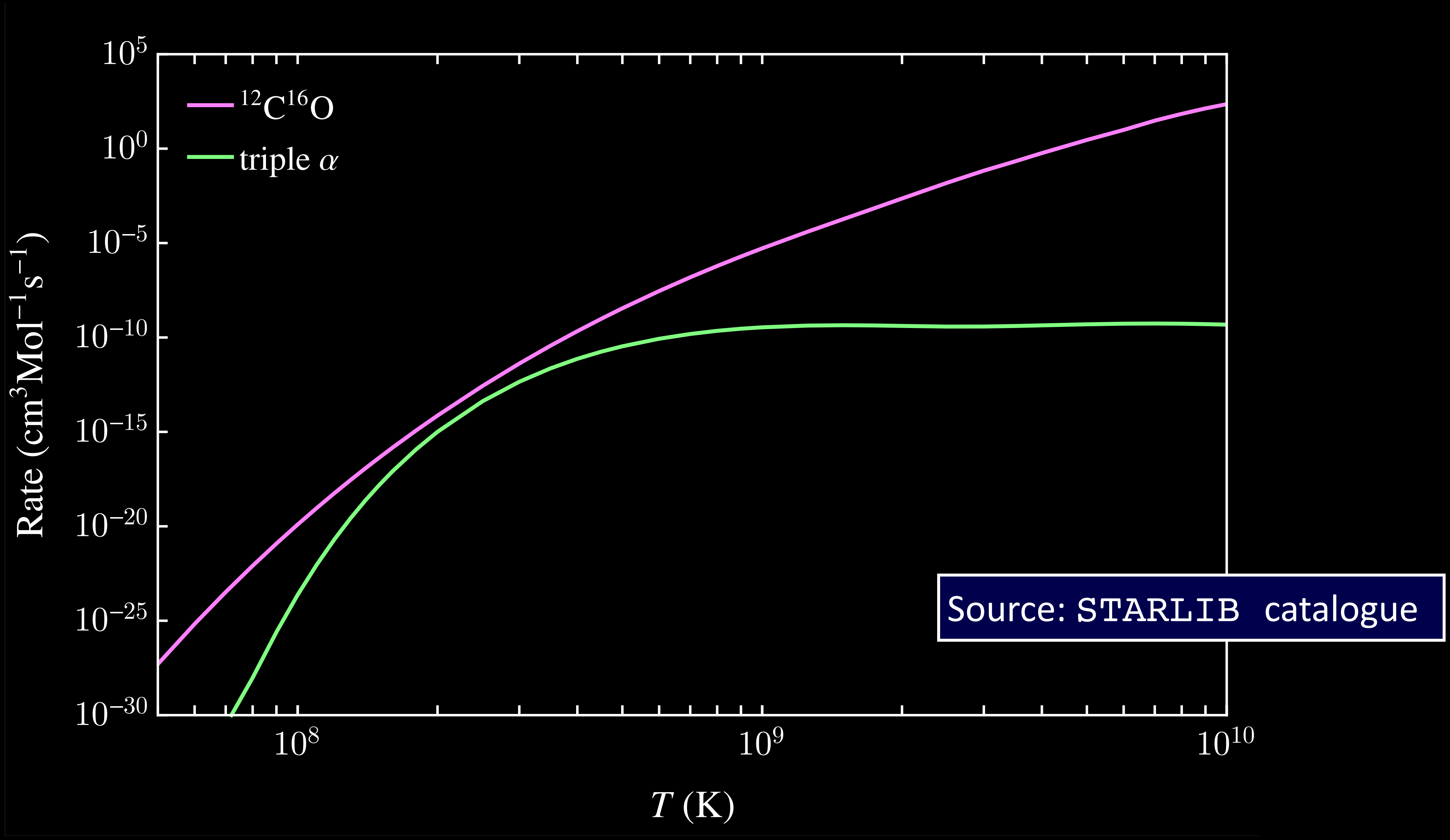
Thank you!

…ask me anything you like!

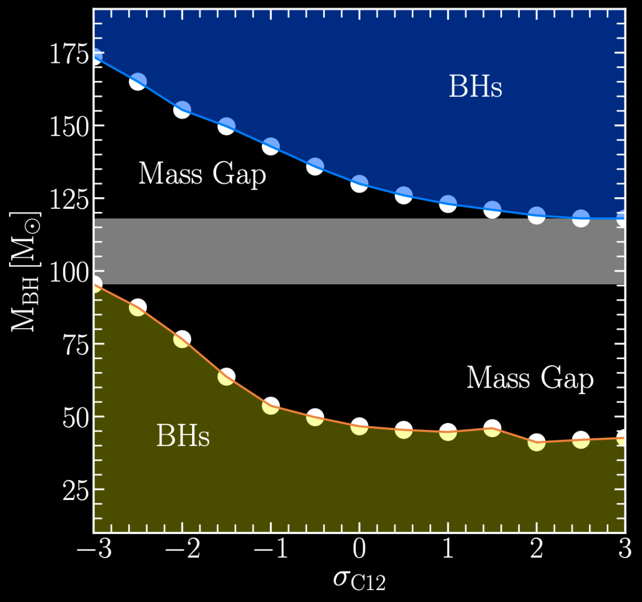
dcroon@triumf.ca | djunacroon.com



Helium burning rates as a function of T

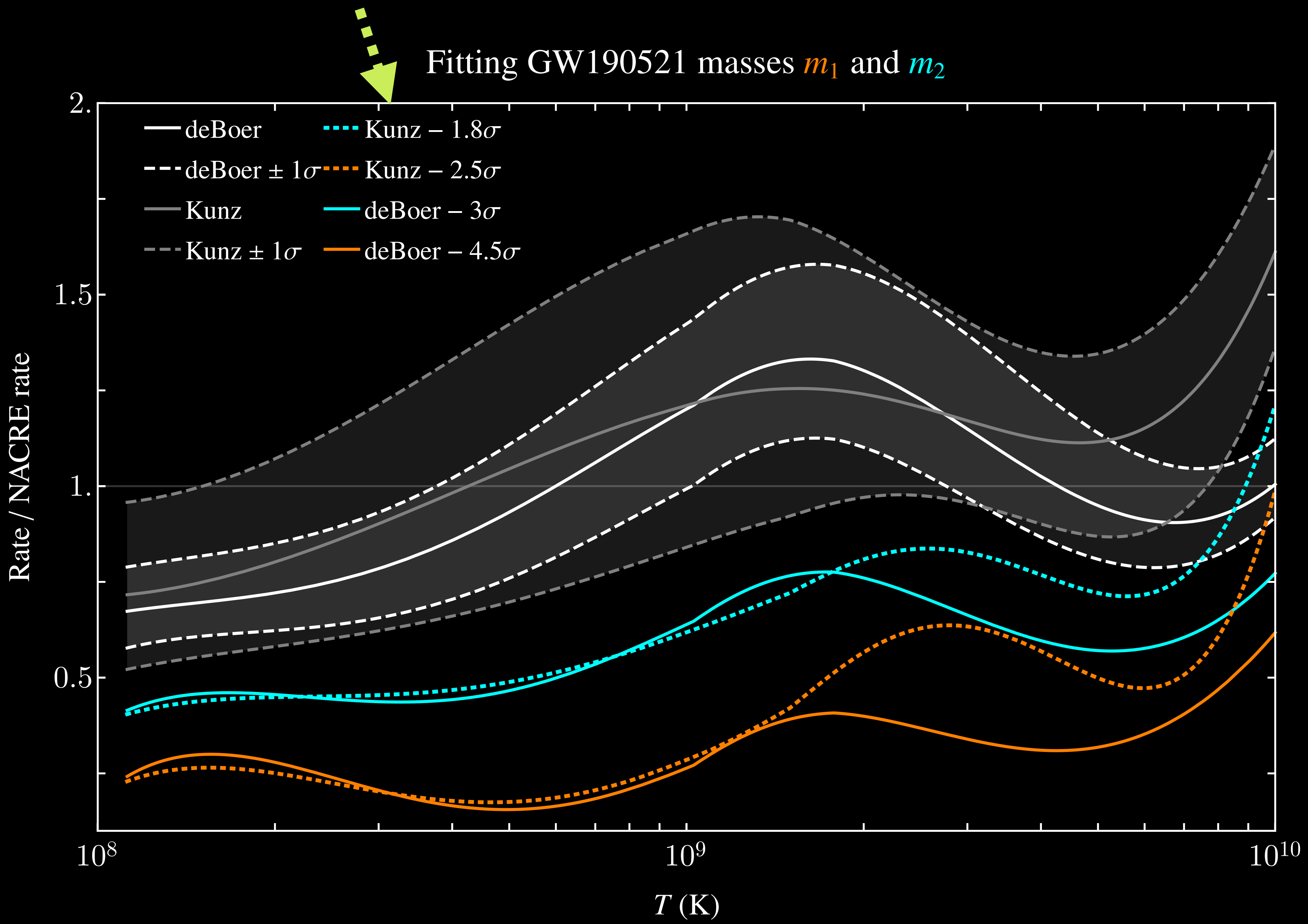


Farmer, Renzo, de Mink, Fishbach, Justham arXiv:2006.06678 [astro-ph.SR]

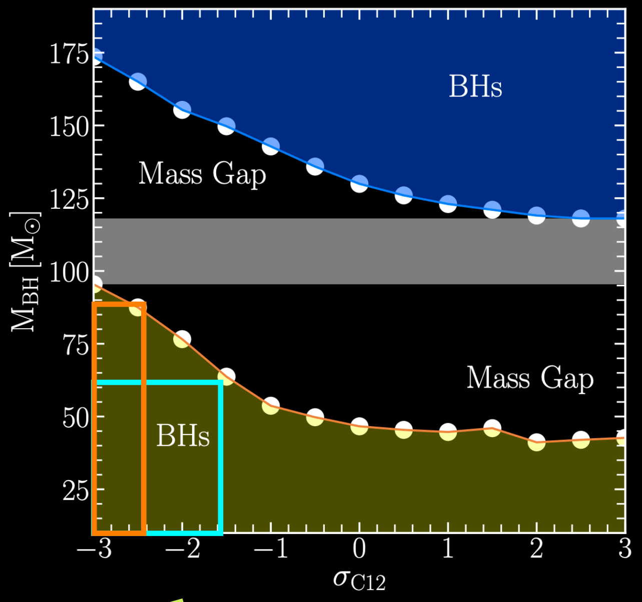


(Kunz is currently used in STARLIB)

Fitting GW190521 masses m_1 and m_2



Farmer, Renzo, de Mink, Fishbach, Justham arXiv:2006.06678 [astro-ph.SR]



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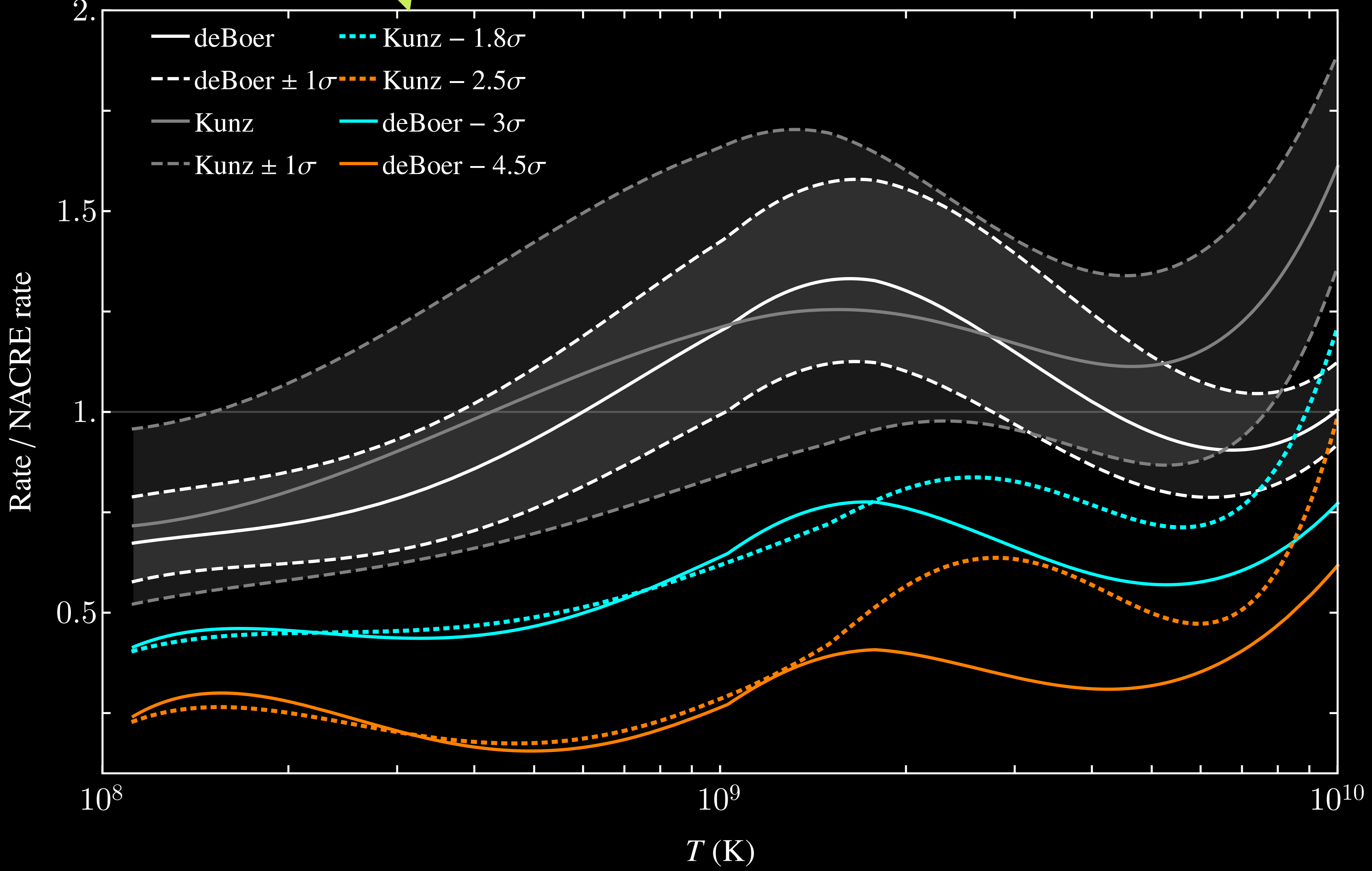
Fitting GW190521 masses m_1 and m_2



Large black hole in LB-1?

- Last year, a $70\,\mathrm{M}_\odot$ black hole was reported in a binary with a high-metallicity smaller star (from the radial velocity variability of the $H\alpha$ emission line, suggesting an accretion disk)
- It was suggested (1911.12357) that it was formed due to the core-collapse of a high metallicity progenitor with reduced stellar winds
- However, those simulations did not include pulsations (they were stopped at carbon burning)
- The observation has since also been disputed (1912.04185 and 1912.03599) - apparent shifts instead originate from shifts in the luminous star's $H\alpha$ absorption line

Binary merger events ($M_1 \approx M_2$)

- >50 LIGO/Virgo observations
  - 2017 Nobel Prize in Physics
- *Can be used to learn about new physics in various ways*
- Most GW radiation from the inspiral phase, ending in $f_{\rm ISCO}$
- Solvable in a (v/c) expansion
  - → Weak gravity, small velocity

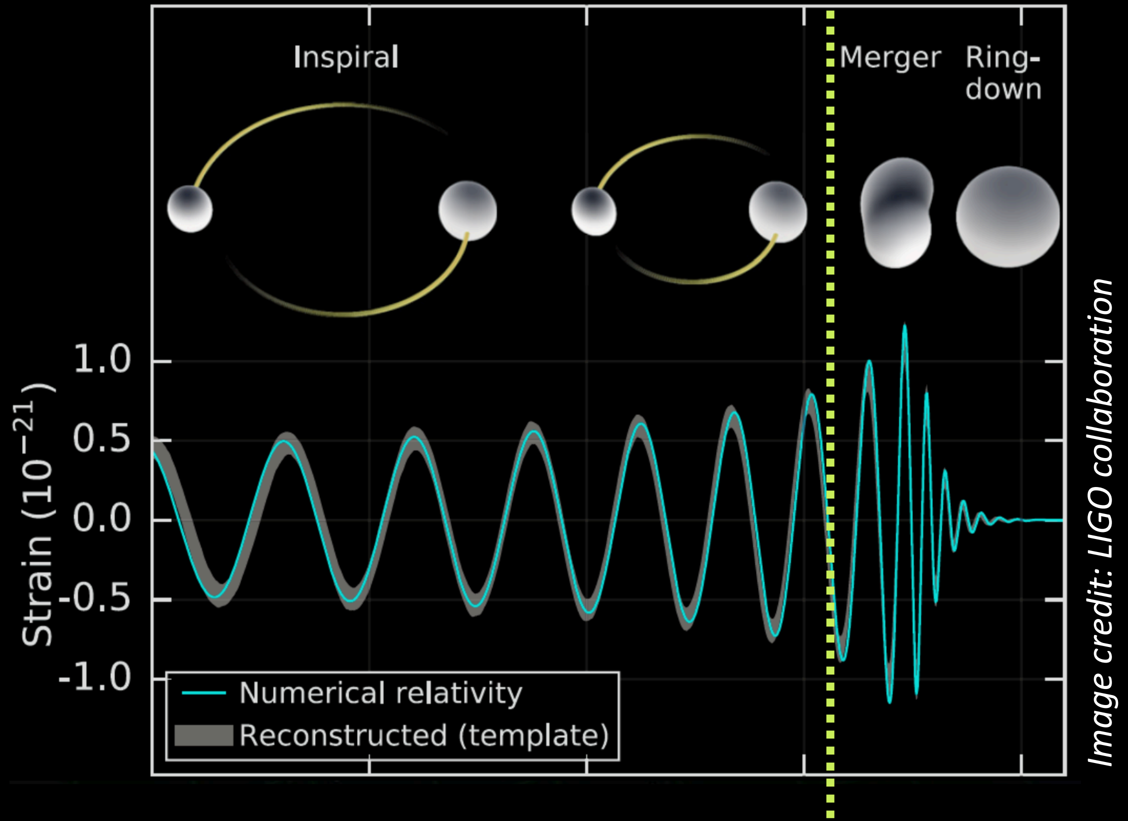


Image credit: LIGO collaboration

$$f_{\rm ISCO} = \frac{C_*^{3/2}}{3^{3/2}\,\pi\,G_N(M_1+M_2)}$$

Compact object merger sensitivity

- Best detection prospects for

$$f_{\min} < f_{\text{peak}} \sim f_{\text{ISCO}} < f_{\max}$$

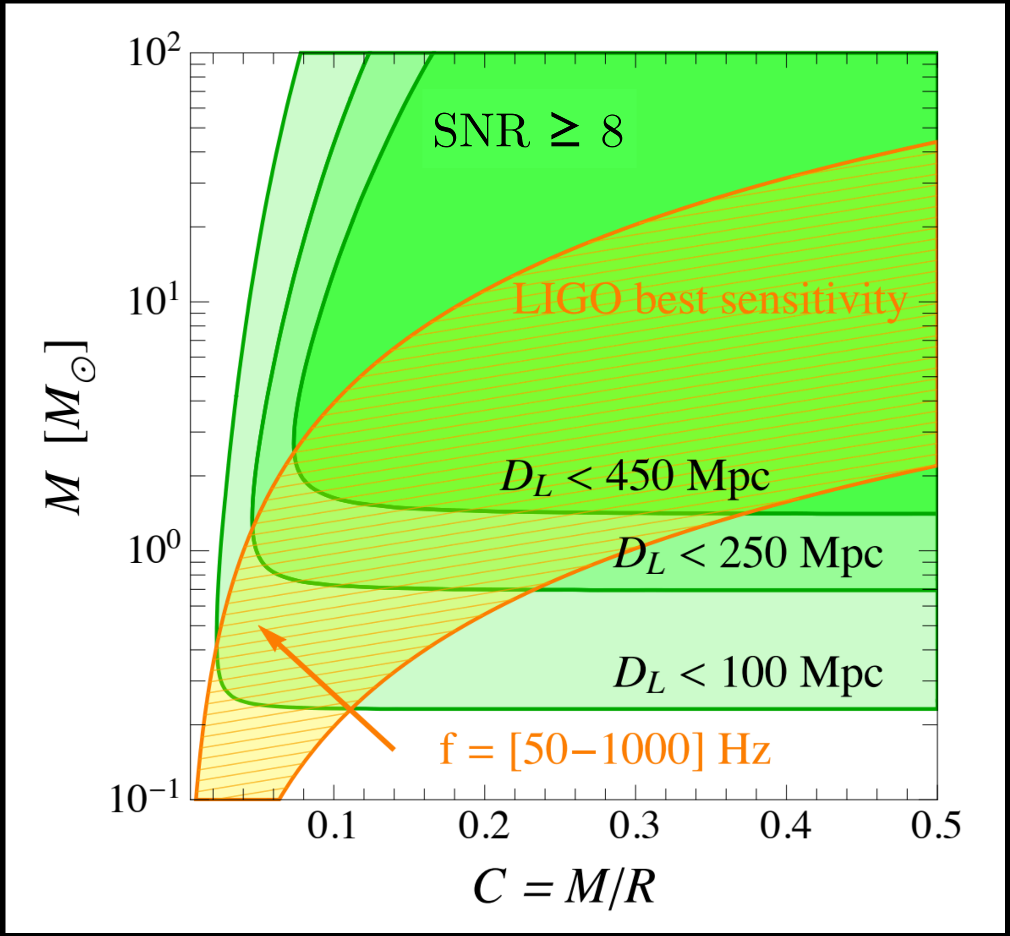
- Defines an CO sensitivity band

$$f_{\text{ISCO}} = \frac{C_*^{3/2}}{3^{3/2}\,\pi\, G_N (M_1 + M_2)} \qquad C_* = \frac{G_N M_*}{R_*}$$

$$C_\odot = 2 \times 10^{-6} \qquad C_{\text{BH}} = 0.5$$

$$C_\oplus = 7 \times 10^{-10} \qquad C_{\text{NS}} \sim 0.1$$

- Sensitivity determined by masses, compactness and luminosity distance



Giudice, McCullough, Urbano [JCAP, 1605.01209]

What can we learn from the inspiral waveform?*

A lot, for example,

1. Component masses
2. Tidal effects → equation of state
3. Dynamical friction → environmental effects
4. Long-range (dark) forces → BSM effects
5. Extra dissipation channels → BSM effects
6. Redshift distribution of events → age of objects
7. “Hair”: multipolar metric deviations (EMRIs) → tests of GR

Hints of mass-gap mergers:

- GW190814 → downgraded mass gap probability <1% → publication June ‘20
- GW190924 (24 September ‘19)
- GW190930 (30 September ’19)

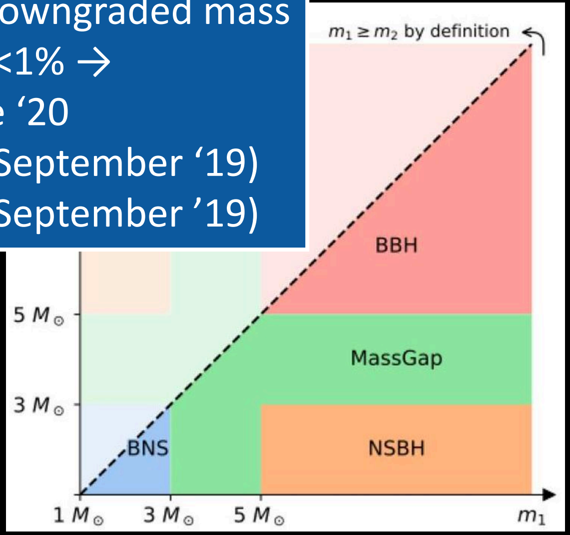


Image credit: LIGO collaboration

So what about new physics? May show up in various ways, I will give a (unabashedly biased) selection of examples

**Further information could come (for example) from multi-messenger signals (or absence thereof), or post-merger quasi-normal modes or “echoes”*